OBSERVATIONAL ANALYSIS OF SHALLOW WATER RESPONSE TO PASSING HURRICANES IN ONSLOW BAY, NC IN 1999

Benjamin L. Speckhart

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Approved by

Advisory Committee

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Chair

Accepted by

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Dean, Graduate School

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ABSTRACT

In the summer of 1999, three hurricanes, Dennis, Floyd, and Irene, passed over the continental shelf of North Carolina in less than a two-month span (Aug. 30 - Oct 17). In the summer of 1999, three oceanographic moorings were deployed at various locations across continental shelf off the coast of North Carolina by North Carolina State University. The moorings that were deployed recorded current velocity, temperature, and salinity data at various depths.

This data, including wind data from the Frying Pan Tower, provided a unique look at the shallow water response to these passing hurricanes. Highly damped inertial oscillations, elimination of stratification, and large Richardson numbers that represented unstable flow will all be discussed in detail in the following thesis.

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Most importantly, I would like to thank Mom, Dad, Joe, Eva, Mike, Jim, Josh, Erin, Joanne, Robb, David, Jonah, and Carissa. My family is the reason I am here and I am absolutely nothing without them.

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INTRODUCTION

Overview

Hurricanes can have enormous impacts on oceanographic processes on continental shelves. However, due to the infrequency of their occurrence, and the unpredictability of their locations and their pathways, staging experiments to document their impacts has been difficult to achieve. Still, they occasionally pass near instrumented mooring sites and measurements have been made [Keen and Glenn, 1999]. This was the case on the North Carolina (NC) coast in the Fall of 1999 when three hurricanes of various intensities, Dennis, Floyd and Irene passed over Onslow Bay, NC over a two-month span. The NC coast has experienced many hurricanes in the past few years, but few have been documented with actual ocean observations. In fact, there are few observations anywhere of the response of the coastal ocean to the passage of hurricanes.

In 1976, Hurricane Belle passed over a highly stratified shelf of the New York Bight. Mayer et al. [1981] describe intense, first mode inertial/near inertial oscillations at depths of greater than 70 m. However, at shallower stations (less than 50 m), only weak heavily damped oscillations were observed in the current records with no corresponding inertial signals in temperature. Inertial/Near Inertial oscillations are known to exist widely within the ocean. They occur when the wind that has been driving a current suddenly ceases to blow. Because of its momentum, the water will not come to rest immediately, and as long as it is in motion, both friction (bottom and/or coastline) and the Coriolis force will continue to act on it. In the open ocean away from any boundaries, frictional forces may be very small so that the energy imparted to the water by the wind takes some time to be dissipated; meanwhile, the Coriolis force continues to turn the water [Brown et al., 2001].

If the Coriolis force is the only force acting in a horizontal direction, and the motion only involves a small change in latitude, the path of the inertia current will be circular. More often, they are seen as clockwise rotating, near circular horizontal currents in the northern hemisphere [Chen et al., 1996].

Local wind forcing primarily generates inertial oscillations, and their strong, vertical shears are a major energy source for vertical mixing [Pollard et al., 1980]. In the coastal region, the amplitude and spatial structure of near-inertial oscillations are constrained by the coastline and modified due to the bottom topography. The amplitude of the oscillations must decrease toward the coast to match the boundary condition of no flow across the coastline [Chen et al., 1996].

At a given location, time-dependent wind stress drives a surface Ekman layer containing inertial oscillations. If the wind stress varies horizontally, vertical velocities due to Ekman suction pump the top of the stratified fluid to produce internal waves. These waves propagate vertically and in shallow water, reflect off the bottom to produce vertical modes. The internal wave response is largest when the spatial and temporal dependence of the wind stress produces resonance with the free internal modes [Mayer et al., 1981].   An example of this inertial temperature response is depicted by Dickey et al. [1998]. Their data show large amplitude temperature oscillations (internal gravity waves near the inertial period) were set up in the seasonal thermocline below the mixed layer. They called the phenomenon inertial pumping.

The main objective of this thesis is to give a detailed observational analysis of the coastal ocean response to passing hurricanes. The following oceanographic processes will be examined: (1) Pre and Post-storm atmospheric and oceanic conditions, (2) The gradient Richardson Number and its representation of stable or unstable flow, (3) Inertial/Near Inertial Current response, (4) Inertial Internal Waves, and (5) temperature response and the effects on stratification.

The Three NC Hurricanes of 1999

Approximately one month before the first of the three hurricanes passed over NC coastal waters, North Carolina State University deployed instrumentation at three sites in Onslow Bay. Moorings 1, 2, and 3, which will be called M1, M2, M3 in this thesis are depicted in Figure 1 & 2. A full description of these instruments is located in the methods section of the thesis.

Each of these three hurricanes elicited different responses from the ocean, which will be discussed later. These data sets are unique because the storms occurred so close to each other and there were instruments in or near their paths. Table 1 summarizes the general parameters of each of the three hurricanes.

Hurricane Dennis passed Onslow Bay on August 30, 1999 with winds reaching 38 m/s and a translation speed of 21 km/hr. Dennis was a Category 2 hurricane on the Saffir-Simpson Scale (http://www.nhc.noaa.gov/

1999dennis.html). The category value for the storms is as they appeared over Onslow Bay. The eye of Dennis was to the east of all three moorings as it passed through Onslow Bay (Figure 1). After its passage through Onslow Bay, Dennis stalled approximately 110 nautical miles east of Cape Hatteras, NC for several days before turning abruptly westward and making landfall on Sept. 4, 1999.

Hurricane Floyd arrived in Onslow Bay approximately two weeks later on September 16th, 1999. Floyd was a weak Category 3 storm with winds between 40-44 m/s and a translation speed of 32 km/hr (http://www.nhc.noaa.gov/1999floyd.html). The eye of Floyd was to the west of all three moorings as it passed through Onslow Bay (Figure 1). As Floyd moved up the North Carolina coast, approximately half the storm was over land and half was over the ocean.

Hurricane Irene passed through Onslow Bay late on October 17th to early on the 18th, 1999. Irene was a Category 1 storm with winds of 29 m/s and a translation speed of 19 km/hr (http://www.nhc.noaa.gov/1999irene.html). The eye of Irene passed between the M1 and M2/M3 moorings (Figure 1).

METHODS

Instrumentation

The three moorings were deployed by N.C. State University starting on July 6, 1999 and were recovered February 28, 2000. They collected data prior to, during, and after all three hurricanes that passed over Onslow Bay in the fall of 1999.

Mooring 1 (M1) was deployed on July 6, 1999 and recovered on February 28, 2000 at 34 23.03 N and 77 23.72 W at a depth of 17 m (Figure 1). The instruments at this mooring included a RD Instruments Workhorse Acoustic Doppler Current Profiler (ADCP) with a frequency of 300 Hz and a microcat (MC) Seabird SBE 37 (Figure 2). The ADCP was placed on the seafloor at about 16.5 m. The ADCP had 30 vertical bins with lengths of 50 cm each. There were 30-minute ensembles with 18 seconds between pings. This instrument sampled east (u) and north (v) current velocity fields. It was recovered 1.2 km from its original location. The MC was also placed on the same mount on the bottom. It sampled temperature, conductivity, and pressure every 15 minutes.

Mooring 2 (M2) was deployed on July 7, 1999 and recovered on February 29, 2000 at 33 44.36 N and 76 45.42 W. The water depth at this location was approximately 50 m (Figure 1). Since the data from this instrument was not used in this thesis, a full description of the instruments will not be given.

Mooring 3 (M3) was deployed on July 6, 1999 and recovered on February 23, 2000 at 33 41.99 N and 76 43.43 W. Here the water depth was 77 m (Figure 1). The instruments used here were two seacats, one electromagnetic InterOcean S4, a workhorse ADCP with a frequency of 300 KHz, and a microcat SBE 37 (Figure 2). The two seacats were located a depth of 15 m and 47 m. These sampled temperature and salinity every 15 minutes. The S4 was located at a depth of 18 m and sampled the same as the instrument M2. However, it failed on November 1, 1999. The ADCP and the microcat were located on the seafloor at about 77 m. This ADCP sampled every 30 minutes, but had 40 bins of 200 cm each. The distance to the first bin was 377 cm. There were 50 pings per ensemble with 36 seconds between pings. The salinity from the 75 m microcat was corrupted past 9/17/99.

Although there was a complete analysis of the data at M2, only the data from M1 and M3 will be used in this thesis. There are two reasons for this:

1. Most of the current data is corrupted from M2
2. M2 and M3 are relatively close to each other and the response from these two moorings is very similar.

It should be noted however, that even though M2 was not used in this thesis, that data (uncorrupted) collected coincides very well with M3. This is good verification that instruments were sampling properly.

Filtering Parameters

All data were filtered using a Butterworth Filter from MATLAB's signal processing toolbox. All data were 3 hour low passed, 40 hour low passed, 400 hour low passed, and 18-24 hour band passed. The *u* and *v* current velocities were rotated 35° counter-clockwise from the *x*-axis (east-west) to correspond to the angle of the continental shelf off the coast in Onslow Bay, NC. Jim Epps, a research technician from N.C State University, in coordination with Dr. Len Pietrafesa, created the Richardson number figures. Their temperature, wind, and gradient Richardson number data were 40 hour low passed using a Lanczos - Cosine filter.

Gradient Richardson Number Equations

The gradient Richardson Number (Ri) is a dimensionless number relating the ratio of buoyancy to inertial forces. In a stratified fluid with characteristic squared buoyancy frequency (N^2), the Ri is defined as a function of height for stratified parallel flows by:

$$\boldsymbol{Ri = N^2(z)/(\delta u/\delta z)^2} \qquad \textbf{(1)}$$

N^2 is the squared buoyancy frequency, (Brunt Vaisala Frequency) and is calculated as follows:

$$\boldsymbol{N^2(z) = (g/\rho)(\delta\rho/\delta z)} \qquad \textbf{(2)}$$

Acceleration due to gravity is represented by *g*. Density at the bottom depth is represented by ρ, and $\delta\rho/\delta z$ is the density gradient between the two selected depths.

Current shear or $\delta u/\delta z$ is the mean horizontal velocity over a depth *z*. For this thesis, $\delta u/\delta z$ was calculated by using the *u* and *v* components of current as follows:

$$\boldsymbol{\delta u/\delta z = [((u(z_1)-u(z_2))^2 + (v(z_1) - v(z_2))^2]^{1/2}/(z_2-z_1)} \qquad \textbf{(3)}$$

A flow is said to be stable if the Ri is greater than 1/4, and if the Ri is less than 1/4 an instability may occur. That is, instability occurs when the velocity shear becomes greater than 4 times the buoyancy frequency as measured by N^2 [Pickard and Emery 1990]. Therefore, the Richardson number provides important quantitative information about the relation between the stabilizing effect of buoyancy and the destabilizing effect of velocity shear. The Ri's that were calculated for this thesis used current data taken from M3 differenced over 6 m and 36 m depths and density data differenced over the 15 m and 47 m depths.

Wind data from Frying Pan Tower (FPT) were collected from the National Data Buoy Center's (NDBC) wind database (http://www.ndbc.noaa. gov/data/download_data.phtml? filename=fpsn7h1999. txt.gz&dir =data /historical/stdmet/). FPT is located at 33.49N and 77.59W (Figure 1) approximately 100 km from M1 and 83 km from M2 and M3. Wind speed and direction values at M1 and M3 most likely vary slightly from the values recorded at FPT. Due to the relative closeness of FPT to the moorings, the wind data do provide an adequate representation of the winds fields at M1 and M3. Sea Surface Temperature's are from AVHRR satellite observations acquired from the John's Hopkins University web site (http://fermi.jhuapl.edu /avhrr/gs/index.html).

THE COASTAL OCEAN RESPONSE TO THE THREE HURRICANES

Hurricane Dennis

Winds at Frying Pan Tower (Figures 3A & 3B):

On August 28 the winds at FPT were light out of the southeast at about 5 m/s. As the day progressed, the wind died down to less than 1 m/s. As the wind speed diminished, it also changed directions from southeast to northeast later on the 28th. The wind vector continued to rotate counterclockwise and increased in speed as well. Mid-day August 30 when the eye of Dennis passed over Onslow Bay, the wind speed reached a maximum of 41.4 m/s from the north/northeast. After the peak wind speed of 41.4 m/s, the wind diminished to 6.3 m/s late on

September 1999. The wind direction in these two days after the storm passed remained from the north/northwest.

Since Hurricane Dennis stalled off the coast of Cape Hatteras, winds of significant strength remained over Onslow Bay for several days. After a minimum of 6.3 m/s, the wind speed increased to between 16 -18 m/s from late on September 2 to early September 5. The wind direction continued to be out of the northwest. The hurricane made landfall on September 4, but the wind vector did not continue its counter/clockwise rotation until early on the fifth. By September 6, the winds were from the south at approximately 13 m/s. The winds remained out of the south at speeds averaging 10 m/s until September 10 when speeds diminished to less than 1 m/s.

Current Response:

Peak velocities at M1 were reached one day after Dennis passed over Onslow Bay on September 1. The along shelf current at 4 m had a southwestward flow that began at 7:00 pm on 8/31/99. A maximum of 74.7 cm/s was reached on September 1 at 6:00 am. The southwestward flow continued through September 3, although with less speed. The response at 9 m (Figure 4) and 14 m was similar. The currents at 9 m (14 m) reached a maximum speed of 68.2 (59.7) cm/s on September 1 at 5:00 am in the southwest direction.

At M3, 6 m (Figure 5), a southwestward flow began on August 29 around 9:00 pm. The current reached a maximum velocity of 144.3 cm/s on August 31 at 5:00pm. The direction remained southwest until September 6 at 5:30 pm. At this time the current direction switched to the northeast. The flow at 36 m reached a maximum of 142.6 cm/s in the southwest direction at 8:00 pm on September 1. The flow here switched to the northwest on September at 4:30 pm. Similarly, at 70 m, the flow reached a maximum velocity of 98.6 cm/s in the southwest direction at the same time as the current at 36 m. The flow also switched directions at the same time.

Salinity Response:

Figure 6A depicts the salinity at M1 at 15 m. The salinity decreased abruptly from 35.1 on August 31 at 4:15 am to 33.2 on August 31 at 5:30 am. The salinity then increased and leveled out at approximately 35.3. After several days off the NC coast, the storm began moving again and the salinity dropped from 35.2 on September 3 at 3:45 am to 34.3 on September 3 at 8:30 am. These spikes in the salinity record are most likely a result of the precipitation associated with Dennis. All along the Onslow Bay coast significant rainfall totals from 6 - 13 inches were recorded during the week that Dennis was off the coast (http://www.nhc.noaa.gov/1999dennis.html).

At M3 (Figure 6B), there was very little change in salinity at 15 m. The biggest response occurred at 47 m. Here an increase in salinity from 36.0 to 36.6 occurred on August 31 at 2:45 pm. There was then an increase from 36.1 on September 1 at 7:30am to 37.1 on September 1 at 11:30 am. The salinity then dropped to 36.1 at 12:45 pm later that day. There was almost no salinity response at 75 m. The salinity at M3 became slightly stratified approximately 3.5 days after the passage of the storm over Onslow Bay with a salinity difference of only 0.2 between the 15 m and 75 m depths.

Temperature Response:

Five days before the passage of Dennis at M1, the sea surface temperature was approximately 29.0 ˚C and the bottom temperature was approximately 27.2 °C. This is a 1.8 °C difference over a 15 m depth. At M1, 15 m (Figure 7A), the temperature decreased from 27.6 °C on August 31 at 7:45 pm to 24.7 °C on September 6 at 12:00 am. Six days after Dennis made landfall, the M1 surface temperature was approximately 26.0 °C and the bottom temperature was approximately 25.0 °C, a 1 °C difference over a 15 m depth.

The sea surface temperature at M3, five days before the storm was approximately 29.0 °C and the bottom temperature was approximately 22.5 °C. This is a 6.5 °C difference over a 75 m depth. At M3 (Figure 7B), 15 m, the temperature decreased from 29.4 °C on August 30 at 4:15 am to 24.7 °C on August 31 at 6:45 pm. The temperature slowly increased and leveled out at 27.2 °C on September 3 at 9:00 pm. At 47 m, the temperature oscillated several times from approximately 20 °C to 26.0 °C from August 28 at 10:45 pm to August 31 at 8:30 am. It then decreased to 19.9 °C on August 31 at 10:00 pm. The temperature gradually increased to 27.2 °C on September 3 and leveled off. At 75 m, between August 31 and September 2, there were significant temperature fluctuations of approximately 5 °C every several hours. Then on September 3, the temperature leveled off at 27.2 °C. At this time the water column became homogeneous. Six days after landfall on September 10, at M3, the surface temperature was approximately 26.0 °C and the bottom temperature was approximately 21 °C, a 5 °C difference over a 75 m depth.

When Dennis passed over Onlsow Bay at M1, the water column cooled 3º - 4 ºC from August 30 to September 6. At M3, there was a completely different response. Figure 8A shows the temperature difference between 15 m and 47 m. The difference in temperature before the storm was 8 ºC, while after the storm, the difference was only 4.5 ºC.

It is clear that the temperature difference at the upper two levels never rebounded to what it was before the passage of the storm. Although Dennis had an impact on the entire water column, it biggest effects in temperature were in the mid/upper layers of the ocean, where stratification was eliminated.

Figure 8B shows the temperature difference between 15 m and 75 m at M3. Stratification is eliminated from September 3 to September 5. Within 12 days of the storms initial passing on September 11, these temperature differences closely rebound to what they were (8 ºC-10 ºC) before the storm.

Richardson Number Analysis at Mooring 3:

In order to get a complete understanding of the Ri response to Dennis, two different time periods will be studied. The first is when Dennis first crossed over Onslow Bay and the second in when it stalled off the coast of Cape Hatteras. Each of these two time periods created varying Ri values (Figure 9B). The main reason for these varying values is because the thermal and current structures vary greatly over the days that Dennis remained over Onslow Bay (Figure 5 and Figure 7B).

The first time period to be analyzed is from August 30 to September 2. On August 30, temperature stratification is at maximum. Since the peak winds at

FPT didn't exist until late on August 30, current shear was not significant enough to cause a drop in the Ri. This is seen in the large Ri values in Figure 9B. However, early on August 30, enough wind stress was imparted on the water column to cause current shear values to increase. This can be seen in the immediate drop in the Ri on August 30. At the same time as this drop in the Ri, stratification is being eliminated (Figure 9A and Figure 9B). The Ri's at this time do not drop to the 0.25 value that is representative of vertical mixing and unstable flow. These values are between 1 and 10. The temperature profile (Figure 9A) clearly indicates that the water column is becoming unstratified. This is the first indication that either large Ri's can representative of unstable flow in the coastal ocean or that in some instances, the Ri is not necessarily a good indicator of vertical mixing. As the winds die down on September 1, so does the stress on the water. Since minimal, current shear decreases, there is a sudden increase in the Ri. This did not last very long.

The second time period to be studied will be from September 2 to September 6. It is during this time period that Dennis stalls off the coast of Cape Hatteras and the wind fields over Onslow Bay increase for the second time. Although vertical mixing is one means by which stratification is being eliminated, it is not the only one.

If a steady wind blows parallel to a Northern Hemisphere coast with land to its right, a downwelling-favorable coastal flow regime will be established. An upwelling-favorable flow results if the coast is to the left of the wind. When a hurricane or an extratropical cyclone approaches a coast at a large angle, the wind is parallel to the coast for extended periods, and a downwelling regime is expected [Swift et al., 1986].

During the seven-day period of Dennis from when it passed through Onslow Bay until it made landfall, the wind direction remained from the north/northwest. This consistent, high velocity, northwest wind caused the net transport of water to be towards the southwest. It can be concluded that the forcing mechanism of the currents was due to the wind at this location. In fact, by 9/1/99 the entire water column down to 70 m is moving southwestward along the NC coast (Figure 5). Since the entire water column is moving in this direction, there must have been a net transport of warmer, unstratified water from the northeast, most likely coming from the Gulf Stream. In Figure 7B and Figure 9B, a slight decrease in temperature at 15 m can be seen as Dennis first crosses over Onslow Bay on from August 30 to August 31. However, on September 1 the entire water column warms. This combination of vertical mixing and net transport of water caused the entire water column to be unstratified on September 2.

This unstratified water column, which was moving in the southwestward direction until September 4, again caused unique Ri values. From September 2 to September 5, Ri's with values of 1 to 10 are dominant. The water column has been completely mixed and therefore the flow at his time is unstable. However, small Ri values are not representative of this instability. Of the three Hurricanes studied, this situation in which buoyancy and shear are at a minimum is an event that is solely unique to Dennis. Although some values in Ri values in Figure 9B are below 1, the dominant Ri values for Hurricane Dennis are from 1 to 10.

Hurricane Dennis created large Ri values at two different time periods during its existence. Large Ri's were created from August 30 to September 1 and from September 2 to September 5. Dennis has shown two interesting aspects when evaluating the Ri and its representation of stable flow. The first is that perhaps large Ri's can be representative of unstable flow. The second being that under certain circumstances the Ri might not be a good indicator of vertical mixing.

This contradicts Church et al. [1989] study of Hurricane Gay. They studied currents and densities in the wake of Hurricane Gay, and recorded Richardson numbers away from the hurricane track that were greater than 1. Within regions of high shear, the Richardson number was found to be small, in some cases less than 1/4. They cited the coincidence between large cooling, large currents, and low Ri's, and suggested that shear flow instability was likely an important mechanism for vertical mixing in the upper thermocline and mixed layer. The main difference between Hurricane Gay and Hurricane Dennis is that the instrumentation used was at a much greater depth for Belle and stratification and shear were not simultaneously at a minimum.

Of the three hurricanes in this study, elimination of stratification and very small current shear is an event unique to Hurricane Dennis. For several days after Dennis the water column was unstable and represented by the previously discussed Ri values. These values are in direct response to the oceanic conditions incurred by the passage of Dennis.

Inertial Current Response:

The wind fields created by Dennis manifested only a minimal inertial response. However, this response was greater than the response from the other two hurricanes. The 6 m across and along shelf currents (Figure 10) show a highly damped inertial oscillation occurring on August 31. The period of this oscillation was approximately 22 hours. This inertial response is very similar to the response of Hurricane Belle [Church et al., 1989]. There was no response in the deeper depths (36 m and 70 m) and thus very little downward propagation of energy in the inertial band. The dominant flows in the across shelf velocities were strictly tidal at the deeper depths.

Since Dennis stalled for several days, steady winds remained over Onslow Bay. It could be concluded that when the hurricane made landfall and the winds relinquished, another inertial response should have been observed at this time. However, due to the fact that temperature stratification was eliminated and there was almost no current shear, Onslow Bay was not conducive to a significant inertial response. Therefore, there was no noticeable inertial response in Onslow Bay after Dennis made landfall, only when Dennis first crossed.

Internal Wave Response:

Figure 7B shows the temperature response at M3. Internal oscillations matching the M2 Semi-Diurnal tidal period of 12.42 hours existed prior to the passage of the storm at 47 m and 75 m. Highly damped inertial oscillations began to occur at 47 m and at 75 m on August 31. However, because of the elimination of stratification, there was only one inertial oscillation of approximately 22 hours for both depths. Mayer et al. [1981] noted no inertial signals could be seen at their mid shelf stations except in the upper levels. They concluded that the influence of the bathymetry was the reason for this low energy response. For Hurricane Dennis, depth of water, short distance from the coastline, and the elimination of stratification were the reasons for the damped internal wave response.

In conclusion, Hurricane Dennis elicited a huge response in Onslow Bay. However, this response was greatest, not as Dennis passed over Onslow Bay, but as it stalled off the coast of Cape Hatteras, NC. During this time period, vertical current shear was virtually eliminated, thus the entire water column at M3 was moving in the southwesterly direction, at very substantial speed and stratification was eliminated. Small shear, along with minimal buoyancy, resulted in a Ri's that had values between 1 and 10. This instability, and bottom/coastline constraint, also eliminated any significant inertial response that would have been associated with this storm.

Hurricane Floyd

Winds at Frying Pan Tower (Figure 11):

From September 12 to September 14 the winds were from the northeast with speeds ranging from 6-12 m/s. It was on September 14, that the initial effects of Hurricane Floyd were being felt at FPT. The winds started to rotate clockwise (because of the location of the station in the wind field) and increase in speed. Late on September 15 winds were from the east/southeast with speeds approaching 25 m/s. The winds continued to rotate clockwise. By mid-day on September 16 the wind speed was 44.5 m/s out of the southeast. Two hours later the wind speed diminished and was out of the southwest at a speed of 37.4 m/s. Again the winds continued to rotate clockwise and diminish in speed and reached a minimum speed of 4.2 m/s at 2:00 am on September 17. At this time the winds were out of the north. The winds remained out of the north with speeds around 3-6 m/s until early on September 19. The winds then flipped directions and came from the south, but remained with speeds of 3-6 m/s. Unlike Dennis, the winds from Floyd diminished to less than 4.2 m/s one day after its passage. Dennis had sustained winds of 16-18m/s for four days after its passage.

Current Response:

At M1 the current flow was weak and oscillating for several days before the storm (Figure 12). However, there was a sudden increase in the speed from 3.7 cm/s on September 18 at 1:00 am to 85.7 cm/s on September 18 at 3:00 am. This response occurred one full day after Floyd had passed through Onslow Bay. The current then changed direction to the northeast on September 18 at 9:30 am. At 9 m and 14 m there were similar changes with respect to direction and speed.

At M3 (Figure 13), 6 m, the current was northeastward starting on September 16 at 9:30 am. Current speeds increased and reached a maximum of 164.7 cm/s on September 17 at 8:30 am. The velocities slowly started to decrease, but remained towards the northeast. The flow then switched directions towards the southwest on September 18 at 9:00 am. At 36 m, the current flow was in the northeast direction starting on September 16 at 12:30 am. The velocities continued to increase, reaching a maximum of 91 cm/s on September 17 at 8:30 am. The velocities then began to decrease, but the flow direction remained in the northeast direction for at least five days after the passage of the storm. There was only a slight increase in speed in the northeast direction for two days before and after Floyd.

The current response at M3 for Floyd is very different than that of Dennis. Unlike Dennis, only the currents in the upper 36 m showed a significant response to the passage of Floyd. This is likely due to Floyd's rapid translation speed and that it did not stall off the coast.

Salinity Response:

M1's salinity (Figure 14A) shows there was an overall increase in salinity from 34.0 on September 12 to 35.0 on September 15 at 10:15 pm. After this increase there was a big drop to 33.0 on September 16 at 9:30 am. Within a day the salinity increased and leveled out to approximately 34.9. Like Dennis, this decrease in salinity was in direct response to rainfalls associated with the storm

There was little response at M3 (Figure 14B) at 15 m and 47 m. A slight drop of 0.5 at 47 m was recorded. The data are corrupted at 75 m. The water at the 15 m and the 47 m depths were just slightly stratified several days after the passage of the storm. Overall the stratification difference slightly decreased between 15 m and 47 m. Before Floyd there was an approximate 0.5 difference and after the storm there was a 0.2 difference.

Temperature Response:

On September 11, five days before the passage of Floyd at M1, the sea surface temperature was approximately 26.0 °C and the bottom temperature was approximately 25.0 °C. This is a 1 °C difference over a 15 m depth. At 15 m, the temperature increased from 24.9 °C on September 14 at 7:15 am to 25.2 °C on September 16 at 8:30 am. There was then a decrease to 24.7 °C on September 18 at 2:15 pm (Figure 15A). Overall there was very little temperature response at this mooring. Four days after Floyd passed, the sea surface temperature was approximately 23.5 °C and the bottom temperature was approximately 24.9 °C. This is a 1 °C increase over a 15 m depth.

Five days before Floyd at M3, the sea surface temperature was approximately 26.0 °C and the bottom temp was approximately 21.0 °C. This is a 5 °C difference over a 75 m depth. At 15 m (Figure 15B), the water temperature increased from 25.7 °C on September 15 at 7:00 pm to 28.5 °C on September 17 at 12:45 am. A 2 °C drop to 26.6 °C followed this on September 17 at 3:00 pm. The temperature then leveled off to 27.5 °C by midday on September 18. At 47 m, the temperature increased from 24.3 °C on September 15 at 7:00 pm to 27.9 °C on September 17 at 8:00 am. The temperature immediately dropped to 22.9°C on September 17 at 7:00 pm. The temperature increased to 27.8 °C on September 18 at 11:45 pm. Two-degree oscillations matching the M2 tide continued for several days after the storm. At 75 m, the temperature increased from 19.2 °C on September 15 at 10:30 am to 25.2 °C on September 17 at 7:15 am. There was an immediate drop to 20.3 °C on

September 17 2:15 pm. The temperature fluctuated back and forth approximately 3 °C for the next five days at a period matching the M2 tide. Four days after Floyd on September 20, the sea surface temperature was approximately 27.0 °C and the bottom temperature was approximately 22.0 °C. This is a 5 °C difference over a 75 m depth.

As Floyd approached Onslow Bay, the temperature difference between 15 m and 47 m (Figure 16A) started to increase to what it was before Dennis. Three days before Floyd the difference was 5 ºC. Just as it seemed the temperature was returning to its pre-Dennis state, Floyd came and eliminated most temperature stratification in the upper 47 meters. After Floyd the temperature difference was 2 ºC-3 ºC. Just like Dennis, this storm minimized the temperature difference in the upper layers of the ocean and it never rebounded to what they were before the storm.

The temperature difference between 15 m and 75 m (Figure 16B) was only minimally affected by the passage of Floyd. There was a difference of 7 ºC-8 ºC three days before the Floyd passed. Although when Floyd hit the temperature difference decreased to 3ºC, it immediately rebounded back to 7 ºC less than a day after its passage.

Richardson Number Analysis at Mooring 3:

Hurricane Floyd was the strongest and fastest moving of the three hurricanes. With winds of 44.5 m/s and a translation speed of 32 km/hr, the affects of Floyd on the ocean were not measured in days like Hurricane Dennis, but rather in hours. In Figure 11, the winds on September 16 were coming from the southeast and rotated in a matter of hours to the southwest. M3 was located to the right side of the eye of Floyd.

Hurricane Floyd's Ri response was very different from the response of Dennis. The biggest contributing factor to this varied response is that the thermal structure of the ocean at M3 was completely different before Floyd than for Dennis. Although the temperature difference between 15 m and 47 m was rebounding to what it was before Dennis, the differences were not as great. Significant stratification existed, but not on the scale of pre-Dennis levels.

Four days before Floyd, (September 12) very large Ri's on the scale 100 to 1000 were present (Figure 17B). Although it was not as stratified as before Dennis, the ocean still had significant stratification (Figure 17A). This accompanied by low shear caused these high values. It can be seen however in Figure 18B that as the storm approached, Ri values became less and less. As wind speeds reach a maximum on September 16, Ri's reach their lowest value. The values produced from Floyd are not like Dennis at all. Here values of .001 are attained. Accordingly, when these values are this level, vertical mixing takes place (Figure 18A). High shear and minimal stratification caused Ri's that were much smaller than that of those for Dennis.

For Floyd, small Ri's below 1 and as small as .001 are representative of unstable flow. It should be noted however, that the period of time of this unstable flow was for less than 24 hours. This is unlike Dennis, in which the instability lasted for several days. The reason for this response is because of the rapid translation speed of Floyd. The result was high winds, but only for a short period of time. In Figure's 17 A & B, it can be seen that the peak winds, vertical mixing, and small Ri's all occur very close to each other. The Ri's created by Floyd are similar to values discovered by Mayer et. al [1981]. For both hurricanes, Ri's below the .25 critical values were created in the storms paths.

In the five days after Floyd it should be noted that small Ri's (below 1) become more and more prominent. After Floyd the temperature differences in the upper 47 meters were very small. Therefore the stratification of this water became less and less. Any significant shear at a time when the buoyancy is small is going to cause small Ri's. After Floyd the frequency of the occurrence of small Ri's began to increase.

Inertial Current Response:

The wind stress on the ocean for Hurricane Floyd did not last very long because of its rapid translation speed. Winds with speeds greater than 30 m/s lasted only about 6 hours, while the entire wind affects from this storm lasted only 24 hours. There was no inertial response associated with this hurricane in the across shelf or along shelf current velocities (Figure 18). Rapid translation speed, bottom/coastline constraint, and small stratification in the upper ocean are the reasons for this lack of response.

Internal Wave Response:

There was no inertial internal wave response associated with Floyd. However, mid day on September 15, approximately 1.5 days before Floyd hit, large temperature oscillations began to occur (Figure 15B). At 47 m there were 2 ºC-3 ºC oscillations, while at 75 m there were 3 ºC-6 ºC oscillations. The period of these oscillations was approximately that of the M2 tide.

Hurricane Floyd clearly elicited a different response than Dennis. Small Ri's occurred only a small period of time during its passage over Onslow Bay and represented vertical mixing. There was no inertial response in the current or temperature data. The most significant response came in the temperature difference between 15 m and 47 m. As seen in previous figures, the temperature difference does not rebound to pre-storm values. It can be concluded that because of its rapid translation speed hurricane Floyd did not have an enormous impact on the current structure of the ocean at M3, but it did significantly impact the thermal structure in the upper 47 meters of Onslow Bay.

Hurricane Irene

Irene Winds at Frying Pan Tower (Figure 19):

Before the passage of Irene, there were variable winds across FPT for several days. From 5:00 am on October 15 until 2:00 pm on October 16 there was a constant 6-12 m/s wind from the northeast. Mid-day on October 16, the wind began a clockwise rotation and began to increase in speed. The winds for a majority of October 17 were out of the southeast and reached a maximum speed of 24.3 m/s at 11:00 pm. Then winds began rotating counterclockwise. By 12:00 am on October 18, the winds were from the north at 20.5 m/s, but slowly diminishing. The winds stopped their counterclockwise rotation at approximately 6:00 pm on October 18 with speeds decreasing from 20.5 NNW m/s to 10.8 m/s WNW during this time. From October 19 to October 20 winds were from the northeast at 7-10 m/s. After October 20 the winds shifted to the south/southeast at 3-6 m/s.

Current Response:

At M1, 4 m, the current flow was in the SW direction for the duration of the storm and no greater than 20 cm/sec. An almost identical response occurred at 9 m (Figure 20) and 14 m.

At M3 (Figure 21), 6 m, the current began to flow southwestward on October 15 at 11:00 pm. The velocities continued to increase, but were northeastward, reaching a maximum of 107.7 cm/s on October 19 at 1:30 am. The flow became southwest on October 19 at 3:30 pm. At 36 m, there was a general northeasterly flow in the current several days prior to the storm. There was a big spike in speed to 91.6 cm/s on October 19 at 4:30 am. The speeds started to decrease but the direction remained northeastward until October 20 at 5:30 pm. There was no significant response at 70 m.

Salinity Response:

The salinity at M1 (Figure 22A) dropped from 34.9 on October 18 at 3:00 pm to 24.9 on October 19 at 12:00 am. Although Irene was weaker than the other two storms, it did cause significant precipitation in the coastal Carolinas. About 2.86 inches of rain fell in Wilmington on October 18 due to Irene (http://www.nhc. noaa.gov/1999irene.html). The big drop in salinity is most likely due to heavy rains associated with Irene. The salinity immediately increased to 33.4 on October 19 at 6:45 am and remained this value after the storm. At M3, the difference in salinities between 15 m and 47 m was 0.7. After Irene passed, the salinities at these depths only differed by .1 (Figure 22B).

Temperature Response:

Three days before the passage of Irene, the M1 sea surface temperature was approximately 23.0 °C and the bottom temp was approximately 22.9 ºC. This is a 0.1 °C difference over a 15 m depth. Virtually no stratification existed. There was very little temperature response associated with this hurricane at M1 (Figure 23A). In fact there was only a 0.5 °C difference directly after the storm passed. Five days after Irene passed, the sea surface temperature was approximately 22 °C and the bottom temperature was approximately 22.4 °C

At M3, three days before Irene, the sea surface temperature was approximately 26.0 °C and the bottom temp was approximately 23.5 °C. This is a 2.5°C difference over a 75 m depth. When Irene did pass over, there was little temperature response at 15 m and 47 m. However, at 75 m, the temperature decreased from 26.5 °C on October 14 at 4:45 am to 22.4 °C on October 15 at 11:45 pm. The temperature then increased to 26.3 °C on October 20 at 11:45 pm (Figure 25B). Five days after Irene passed, the sea surface temperature was approximately 26.0 °C and the bottom temperature was approximately 26.5 °C. This is a 0.5 °C increase over a 75 m depth.

Although it was not as large, Hurricane Irene had very similar effects on the upper ocean thermal structure as the two previous storms. Before Irene hit, the temperature difference between the 15 and 47-meter depths was only 2 ºC-2.5ºC (Figure 24A). This small difference is due in part to the previous storms eliminating stratification in the upper layers and the seasonal cooling cycle of the ocean, in which temperature differences will decrease anyway. After Irene the difference was only about 1 ºC-1.5 ºC. Even though this is not as great, it is significant and shows a relationship between the three hurricanes. The 15 m and 75 m temperature difference (Figure 24B) does not immediately rebound to what it was before the storm. In fact, five days after the storm, the temperature difference between the 15 and 75-meter depths is only 1 °C. It took approximately a week and a half for the temperature difference to rebound to its pre-Irene state.

Richardson Number Analysis at Mooring 3:

Hurricane Irene was the weakest of all three hurricanes and therefore elicited the least oceanic response. Hurricane Irene created Ri's that were very similar to the ones created by Hurricane Floyd. As with Floyd, the thermal structure of the ocean at M3 was very different before Irene. Minimal stratification on the scale of 1 ºC to 1.5 ºC existed before the passage of Irene.

Three days before the passage of Irene on October 14, very large Ri's existed (Figure 25B). Even though stratification was at a minimum, current velocities were at a minimum as well (Figure 21). This combination caused these high values. As the storm approached, Ri's began to decrease and hovered around 1 to 5 from October 15 to October 17. Then mid-day on the October 17 peak winds from Irene were created. It was at this time Ri's dropped to below 1 and reached lows of .001. Although it was not as significant as Floyd, these small Ri values are accompanied by the slight vertical mixing seen in Figure 25A.

These values remained small because stratification between 15 m and 47 m was virtually eliminated for 1.5 days after Irene. On October 20, when stratification slightly increases, so do the accompanying Ri's.

In some ways the Ri response to Irene was almost identical to Floyd. Peak winds, small Ri's, and vertical mixing all occurred nearly at the same time (Figure's 25 A & B). Just like with Floyd, in the days after Irene, small Ri's are seen periodically through the record. Stratification at 15 m and 47 m was now even less than it was for Floyd. Therefore, any shear will cause Ri's to drop significantly.

Inertial Current and Internal Wave Response:

There is no evidence of inertial response in the current (Figure 26) or the temperature records. Internal waves existed, but were dominated by the M2 tide (Fig 23B).

Irene elicited very little response from the coastal ocean. Minimal stratification existed before Irene hit, so there was not as great a temperature response. The greatest response was in the salinity record, where a big drop indicated the heavy rains associated with Irene.

DISCUSSION

Three different hurricanes passing over the same instrumentation in such a short period of time provided a unique data set. For each of these three storms the response was different because of different wind distributions, varying states of stratification, translation speeds, relationship to the moorings, and duration spent over Onslow Bay.

The response to Dennis was the most significant of all three of the hurricanes. The eye of Dennis passed to the right of all the instrumentation and a large percentage of the hurricane was over the ocean when it passed over Onslow Bay. The main reason for the huge impact of Dennis is that it stalled off the coast giving it more time to influence the coastal ocean.

This produced constant, relatively high velocity winds from the northwest that remained over Onslow Bay for about six days. The stress imparted by these winds was able to move the entire water column southwestward for five days. This movement imported unstratified water along with vertical mixing eventually mixed the entire water column, eliminating stratification for four days. Due to its closeness, it is likely that this imported water came from the gulf stream. Elimination of stratification and minimal current shear caused large the Ri's discussed earlier.

The data examined clearly showed the temporary impact one storm has on the thermal structure of the coastal ocean. It also shows how three storms in succession can permanently (over the period of this observation) alter the temperature structure as well.

As mentioned above, the thermal structure of the ocean was severely manipulated by Dennis at both M1 and M3. Figure 28 shows the M1 temperature from Dennis to Irene. Overall there is approximately a 6 ˚C drop in temperature during the time period of these storms. After an overall cooling of 3.0 °C at M1, the decrease in temperature until Irene is linear, indicating the seasonal cooling cycle of the ocean. The elimination of stratification at M3 shows the severe impacts of Dennis. However, even with the state of the water column after Dennis, it is evident in the M3 temperature profiles that the water temperatures at this mooring were rebounding to the pre-Dennis state.

However, because of Hurricane Floyd the ocean never did completely rebound. Floyd's timing is very important in understanding the overall impact of the three storms. Although Dennis had more of an immediate oceanic impact, the lasting change (period of the three hurricanes) in the oceans thermal structure was due to Floyd hitting at the time it did. If by chance, Floyd hit two weeks later, the pre-Dennis and pre-Floyd temperature conditions may have been very similar. Floyd is the reason why the upper 47 m of the ocean at M3 became less stratified for the period of this observation. It is important to understand that even though stratification was being eliminated, overall, the water column was warming as a result of gulf stream moving closer to the coast (Figure 29).

The interaction between Dennis and Floyd also affected the inertial response associated with significant wind events. When the ocean was highly stratified before Dennis, a highly damped inertial response was observed. However, since only a minimal stratification existed before Floyd, there was no noticeable inertial response associated with Floyd. Floyd's rapid translation speed also contributed to this lack of inertial response.

Irene was the weakest of all three hurricanes and therefore elicited the least response. Just like Floyd, the thermal structure varied greatly before Irene compared to the other two hurricanes. This hurricane, though, virtually eliminated any remaining stratification in the upper ocean.

The data discussed in this thesis unveiled oceanic responses that mirrored previously documented hurricanes and responses that are unique to Onslow Bay. Of major importance are the large Ri's that were produced in the coastal ocean associated with Dennis. These Ri's were set up by a unique situation in which stratification and current shear were minimal at the mooring's location.

The other topic of importance is that there is now data that represents how hurricanes not only affect the thermal structure of the ocean, but how storms can actually interact and affect each other. In the Fall of 1999, the thermal structure of the ocean was completely altered due to the three hurricanes. The data presented in this thesis clearly show the impacts hurricanes can have on the coastal ocean not only for days, but for months as well.

Table 1: General Hurricane Parameters

	Hurricane Dennis	**Hurricane Floyd**	**Hurricane Irene**
Dates of Occurrence	8/30/99 - 9/4/99	9/16/99 - 9/17/99	10/17/99-10/18/99
Category	2	3	1
Max. Wind Speed at FPT	38 m/s	44 m/s	29 m/s
Translation Speed	21 km/hr	32 km/hr	19 km/hr
Distance from eye to M1	115 km East	16 km West	86 km East
Distance from eye to M2	25 km East	100 km West	6 km West
Distance from eye to M3	20 km East	105 km West	11 km West

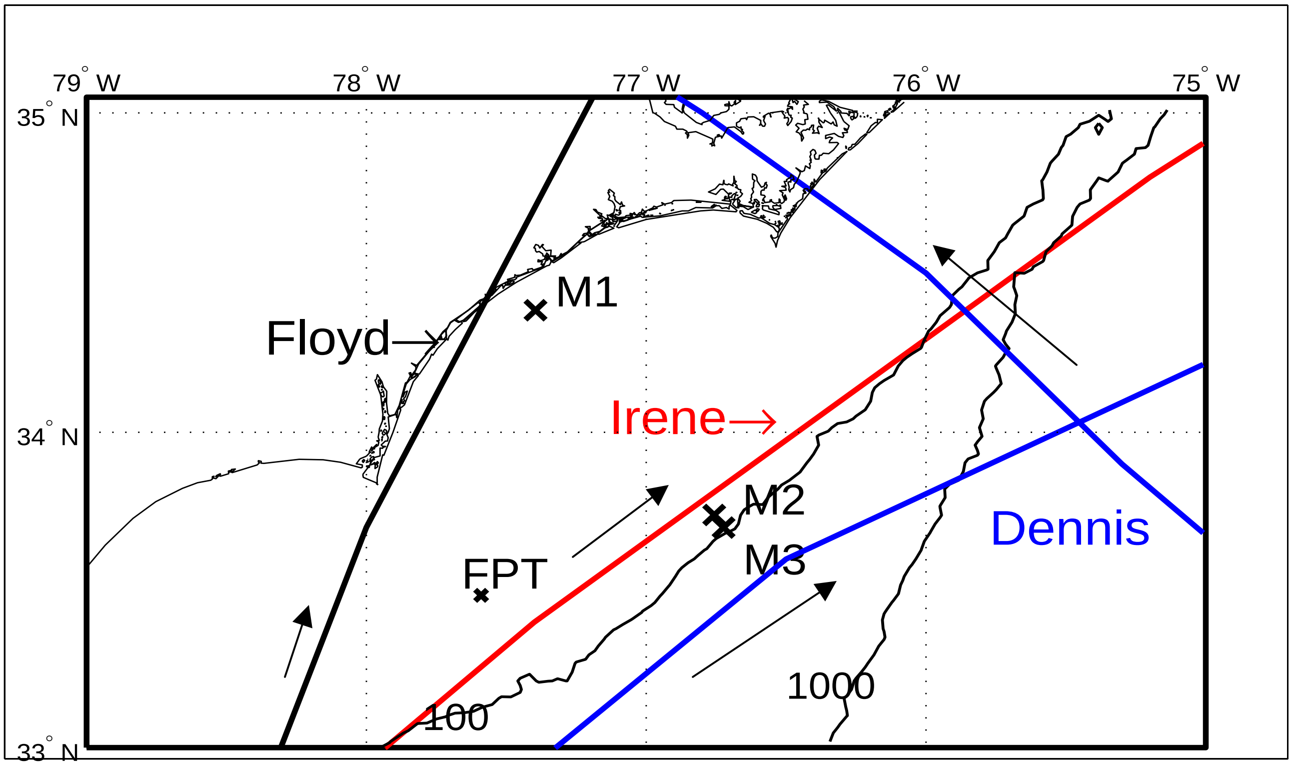

Figure 1: Hurricane Paths and Mooring Locations (black arrows pointing in the direction the hurricane traveled)

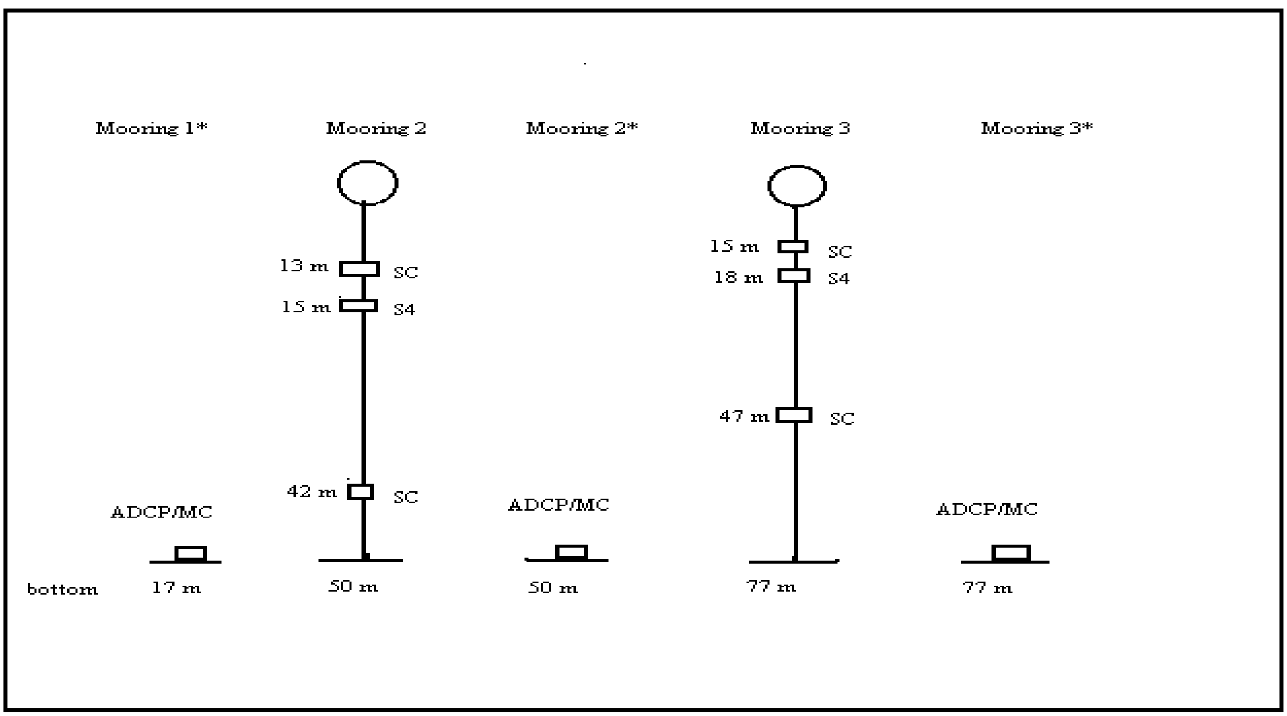

Figure 2: Instrumentation and their orientation on the three moorings

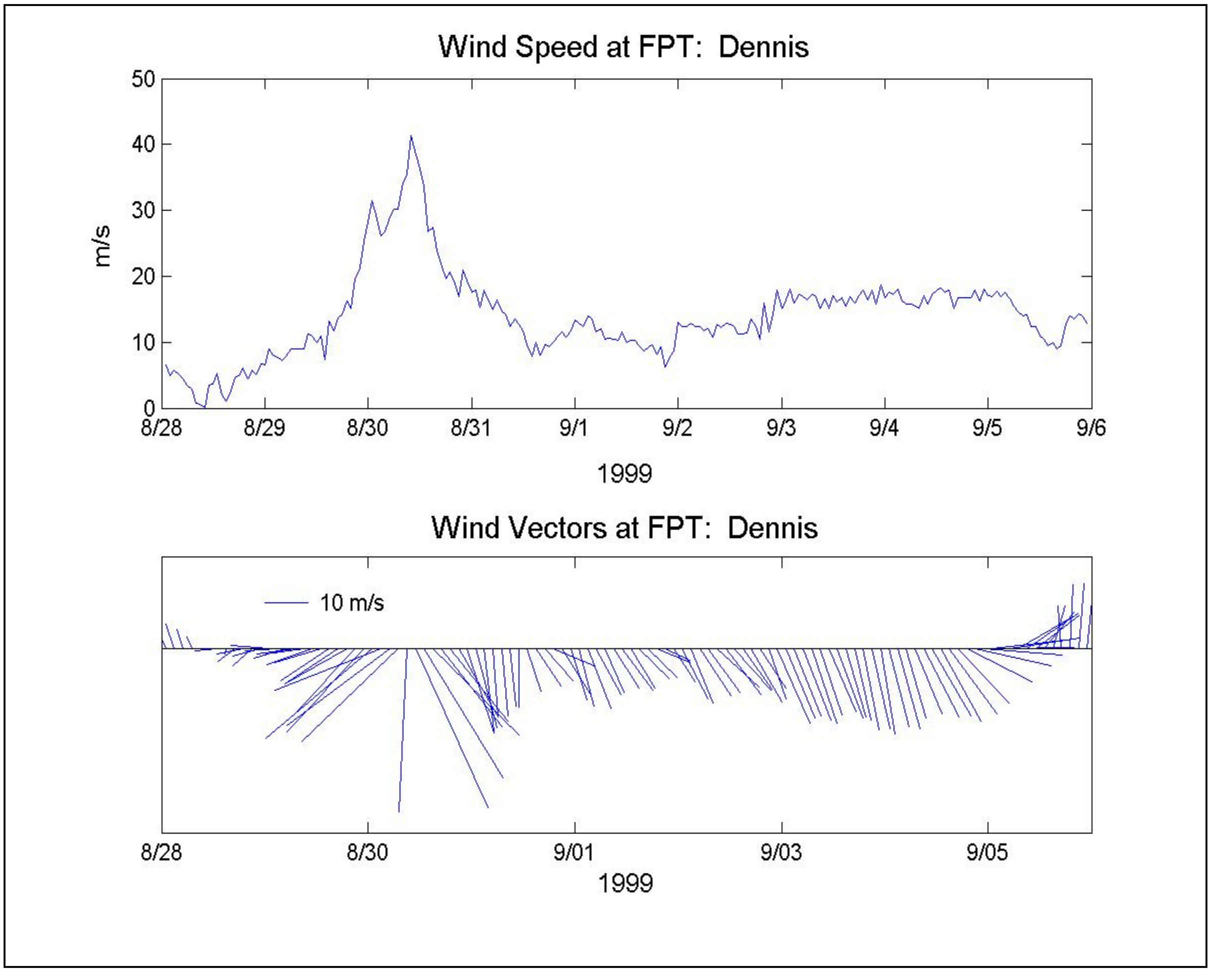

Figure 3: (Top) Hurricane Dennis Wind Speed and (Bottom) Wind Vectors at FPT (north/south is the vertical and east/west is the horizontal)

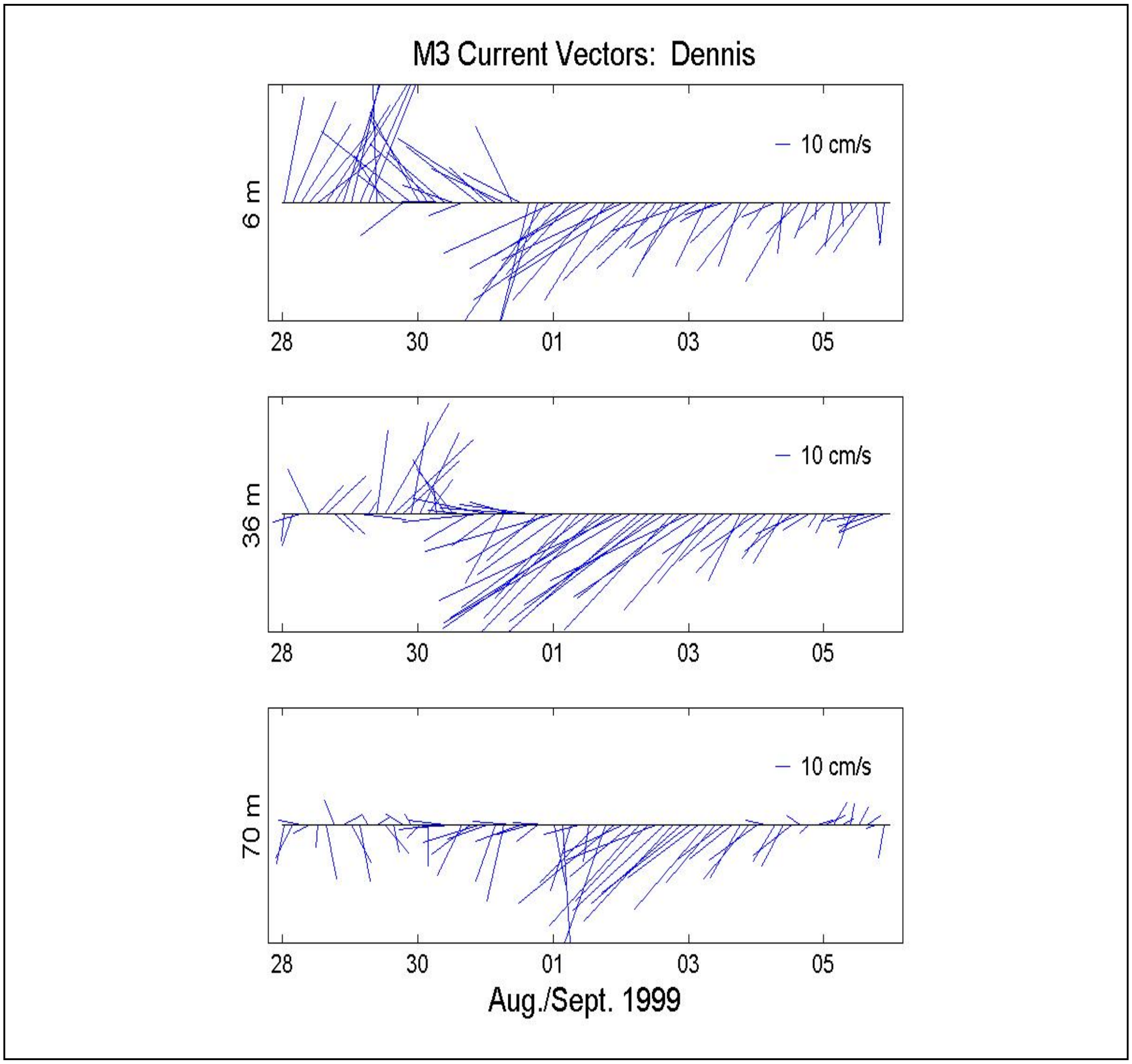

Figure 5: Hurricane Dennis M3 Current Vectors (3 hour low pass, north/south is the vertical axis and east west is the horizontal axis)

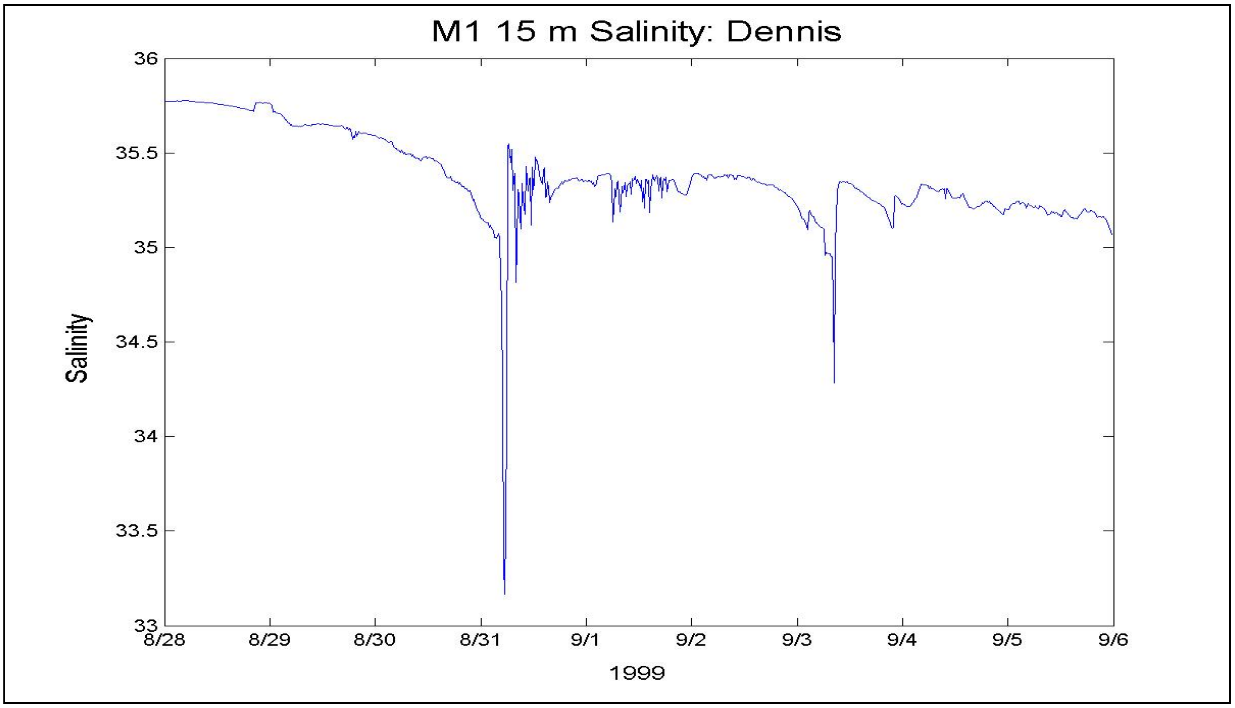

Figure 6A: Hurricane Dennis M1 Salinity

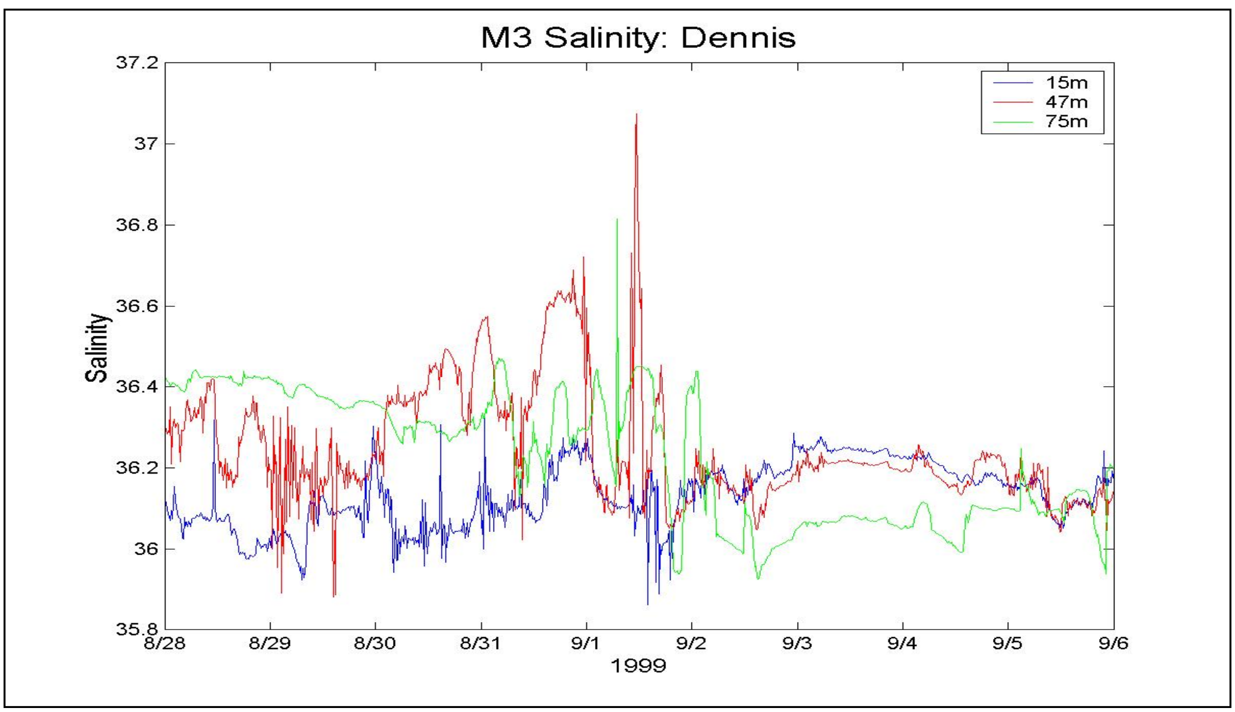

Figure 6B: Hurricane Dennis M3 Salinity

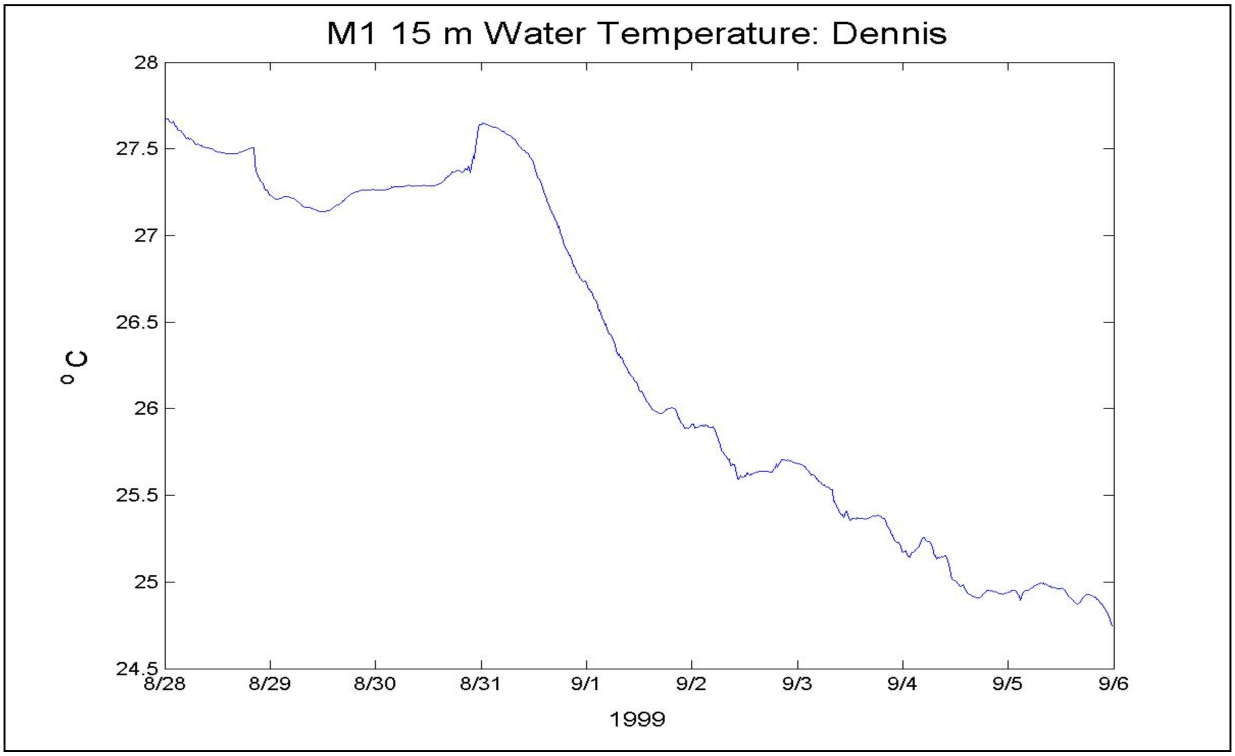

Figure 7A: Hurricane Dennis M1 Temperature

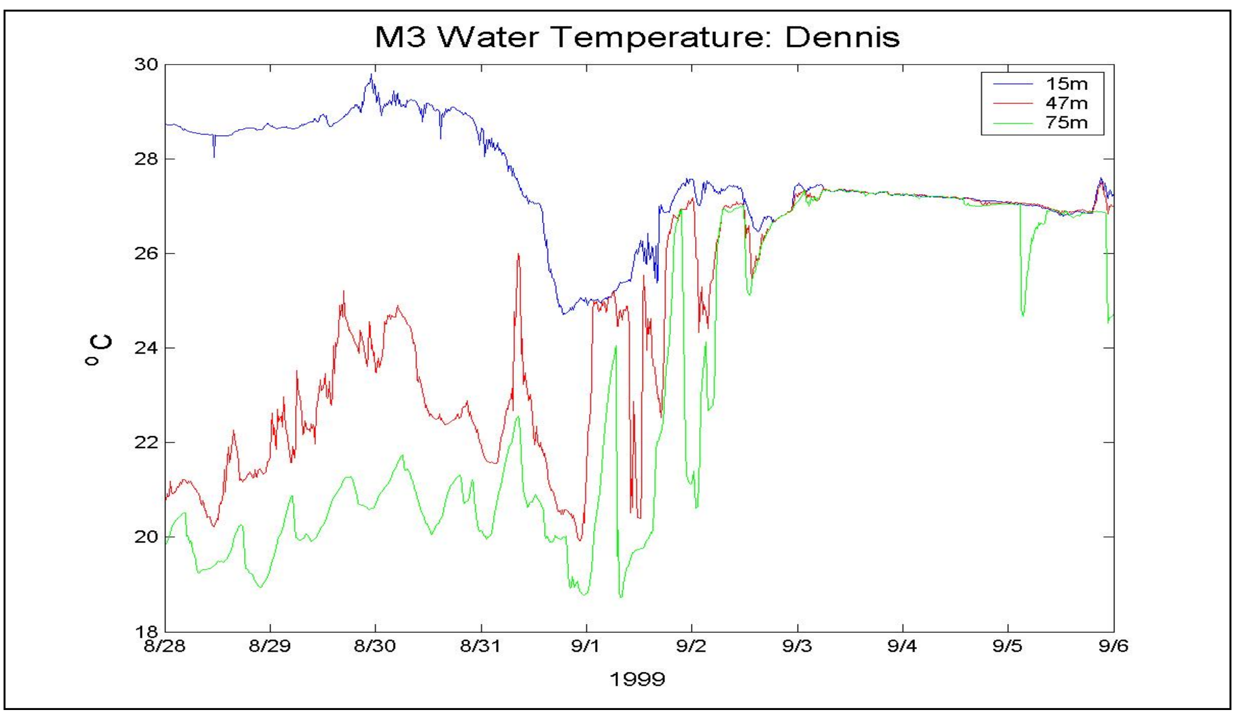

Figure 7B: Hurricane Dennis M3 Temperature

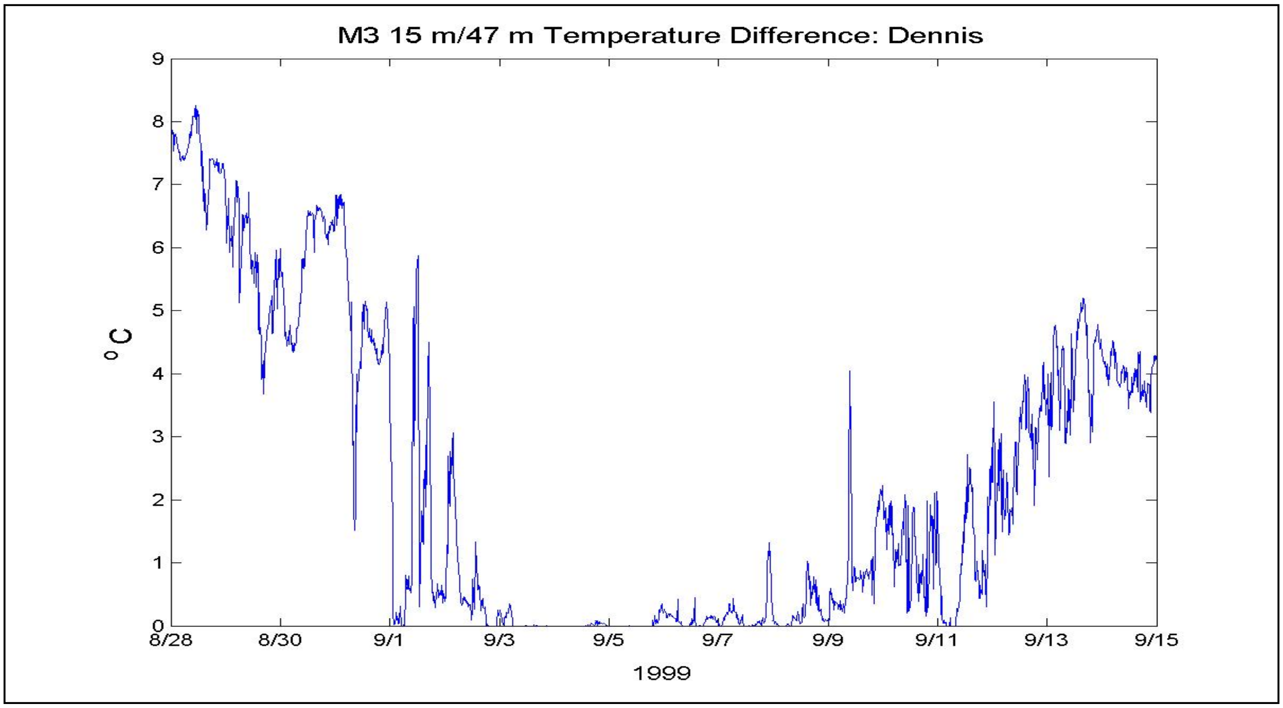

Figure 8A: Hurricane Dennis M3 15 m - 47 m Temperature Difference

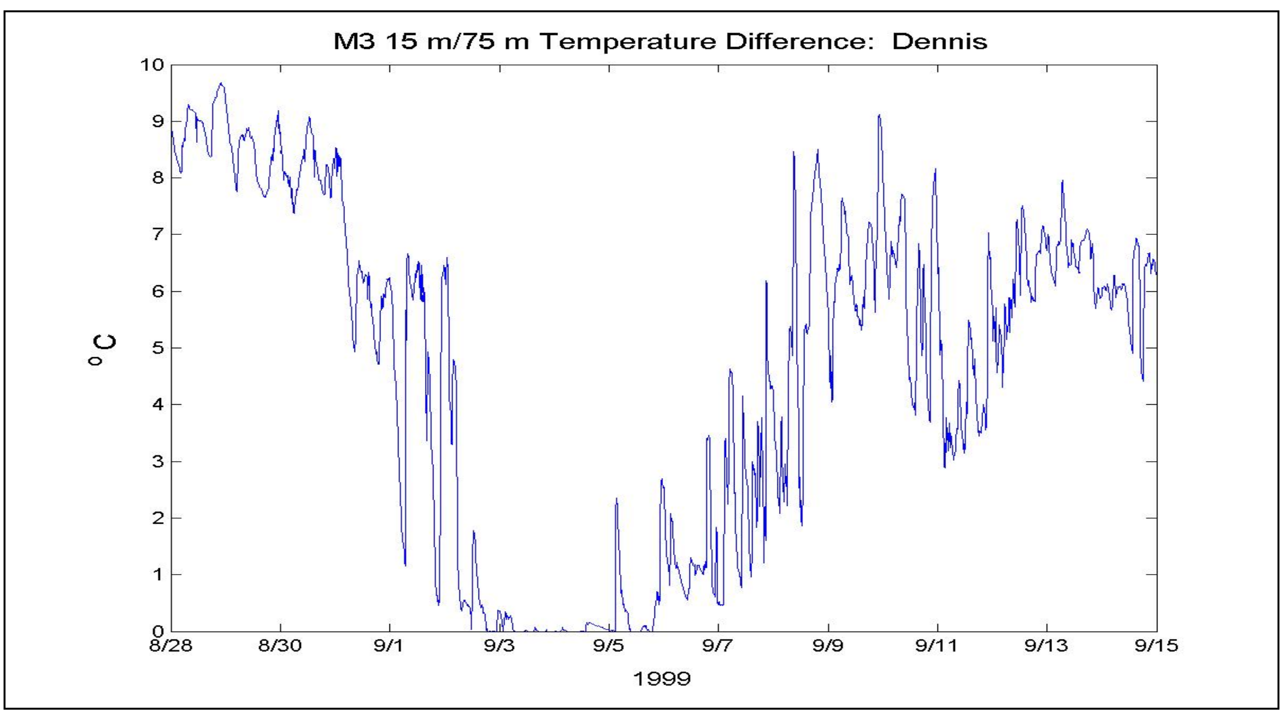

Figure 8B: Hurricane Dennis M3 15 m - 75 m Temperature Difference

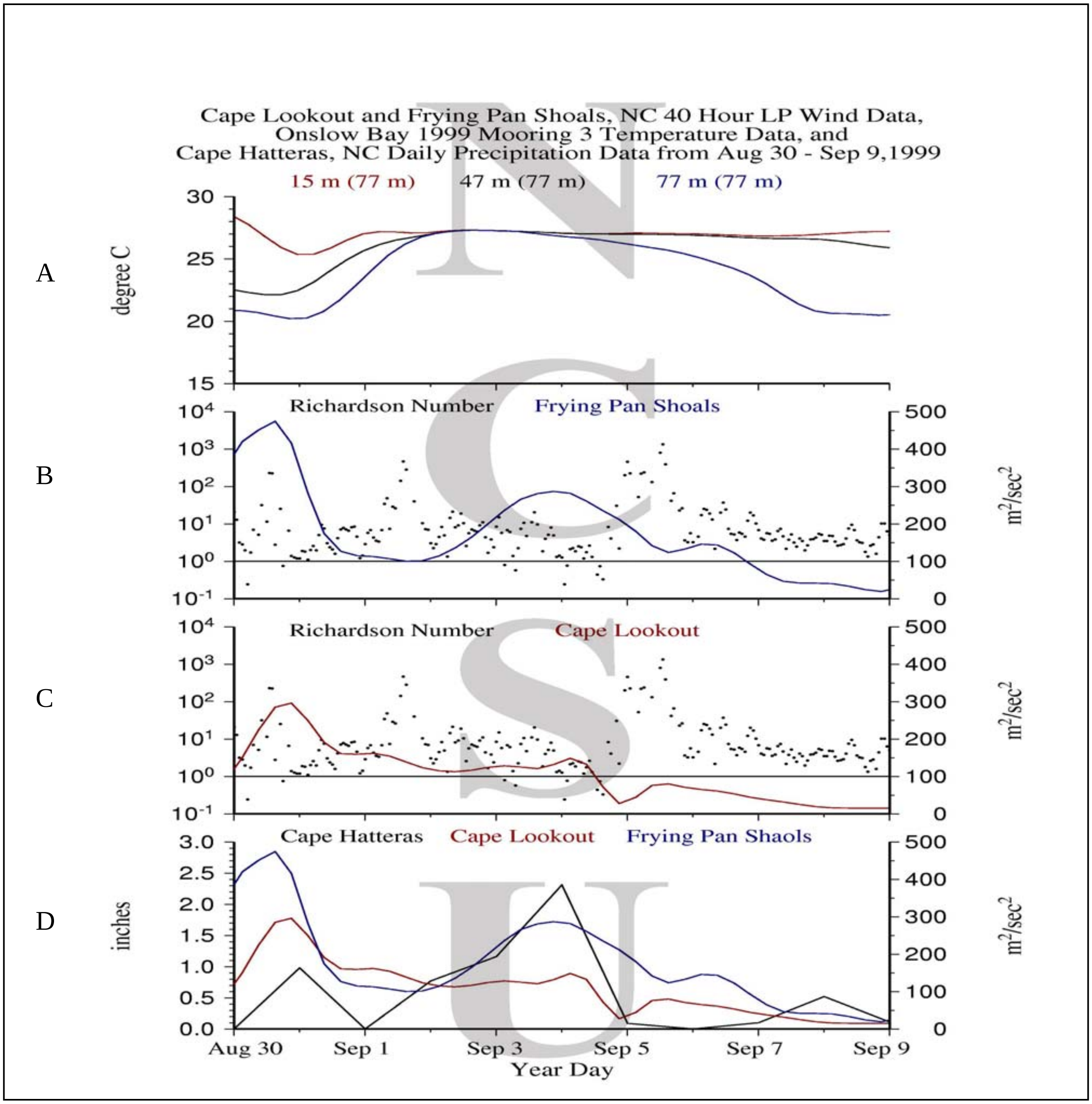

Figure 9: All plots are 40 hour low pass (9A) Hurricane Dennis M3 Water Temperature, 15m (red), 47 m (blue), 77 m (black); (9B) M3 Richardson number between 6 m and 36 m, black dotted line indicates Ri, blue solid line is the kinetic energy of the wind speed at FPT; (9C) M3 Richardson number between 6 m and 36 m, black dotted line indicates Ri, blue solid line is the kinetic energy of the wind speed at Cape Lookout; (9D) Blue line is the kinetic energy of the wind speed at FPT, Red line is the kinetic energy of the wind speed recorded from Cape Lookout (station CLKN7), Black line is the precipitation from recorded from NOAA's NCDC station located at Billy Mitchell Airport on the island of Hatteras, NC

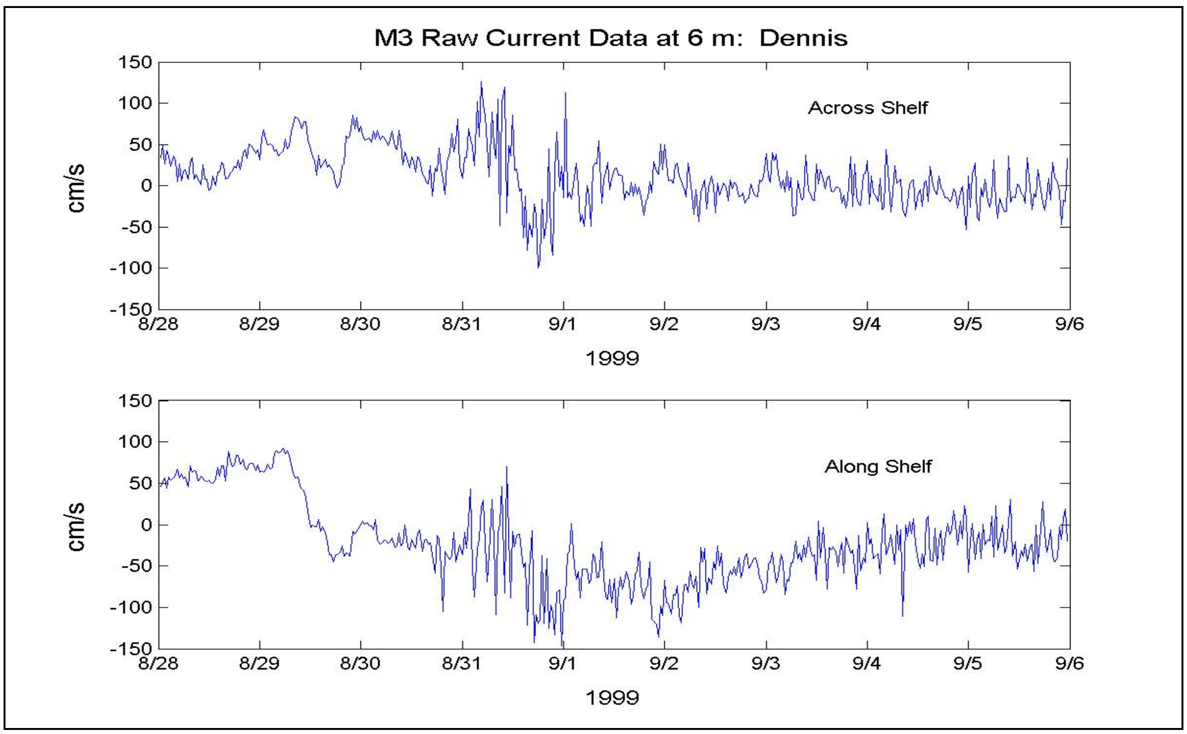

Figure 10: Hurricane Dennis M3 Raw Current Data (rotated 35˚ counter-clockwise from the x axis)

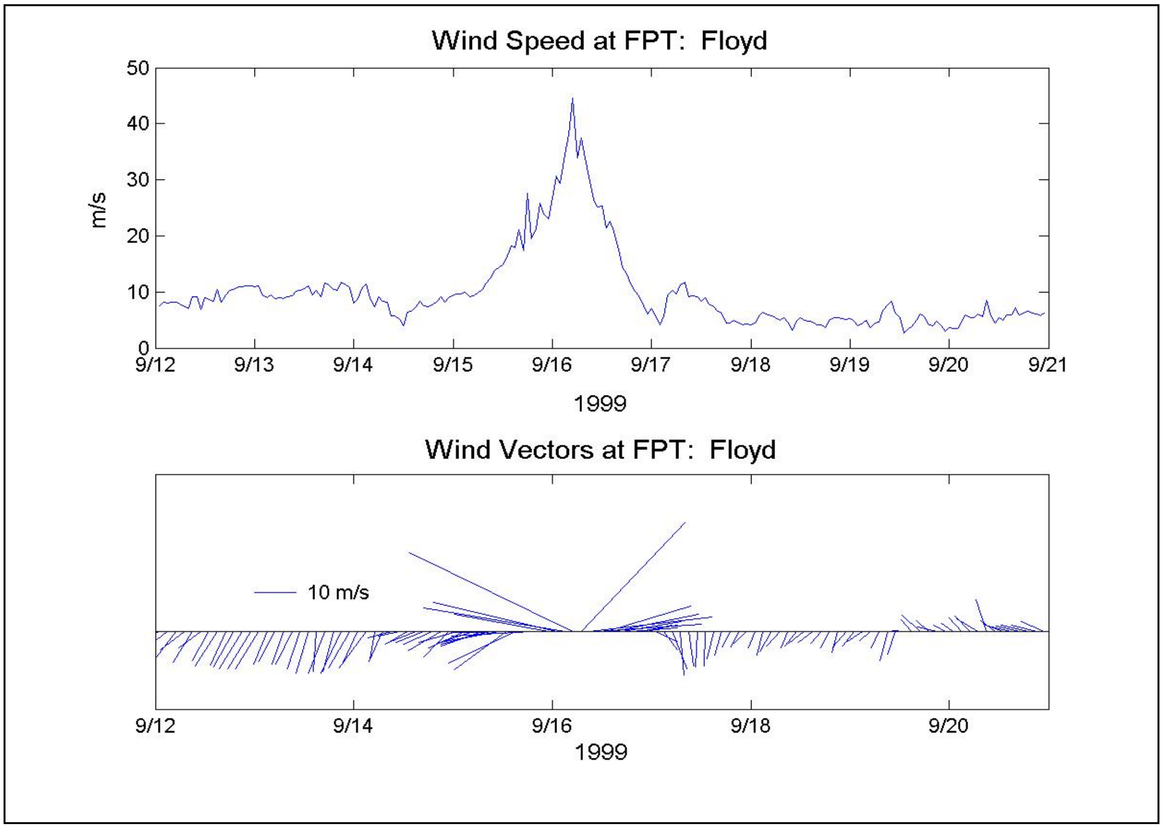

Figure 11: (Top) Hurricane Floyd Wind Speed and (Bottom) Wind vector (north/south is the vertical axis and east/west is the horizontal axis)

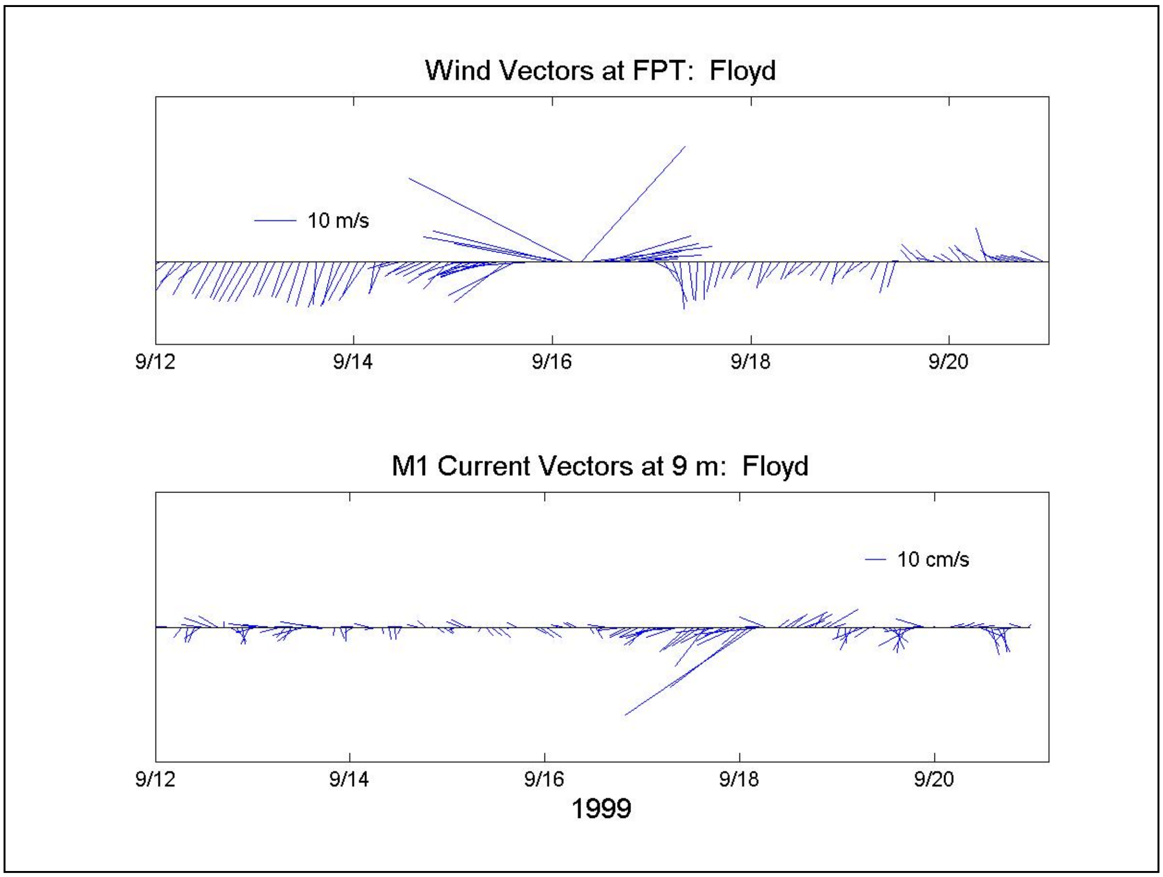

Figure 12: (Top) Hurricane Floyd Wind Vectors and (Bottom) M1 Current Vectors at 9 m (north/south is the vertical axis and east/west is the horizontal axis)

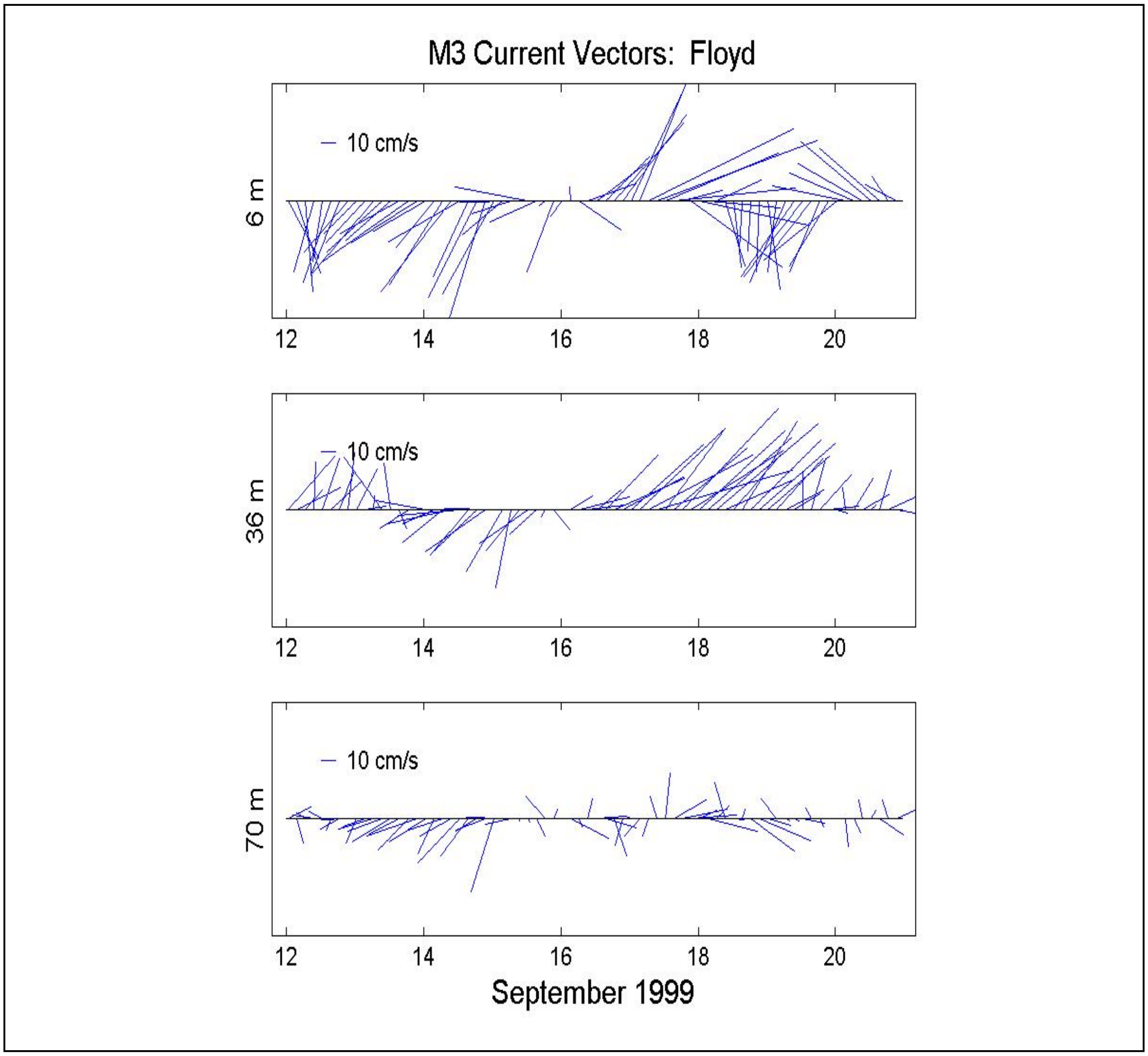

Figure 13: Hurricane Floyd M3 Current Vectors (3 hour low pass, north/south is the vertical axis and east west is the horizontal axis)

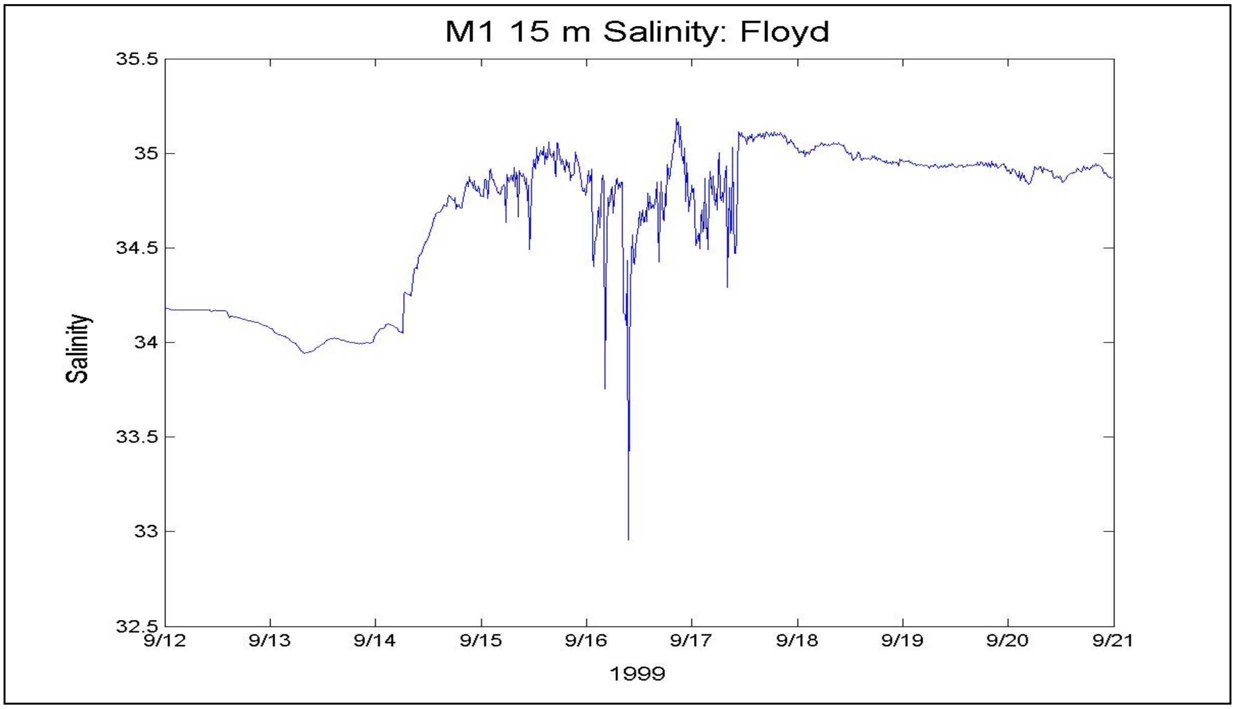

Figure 14A: Hurricane Floyd M1 Salinity

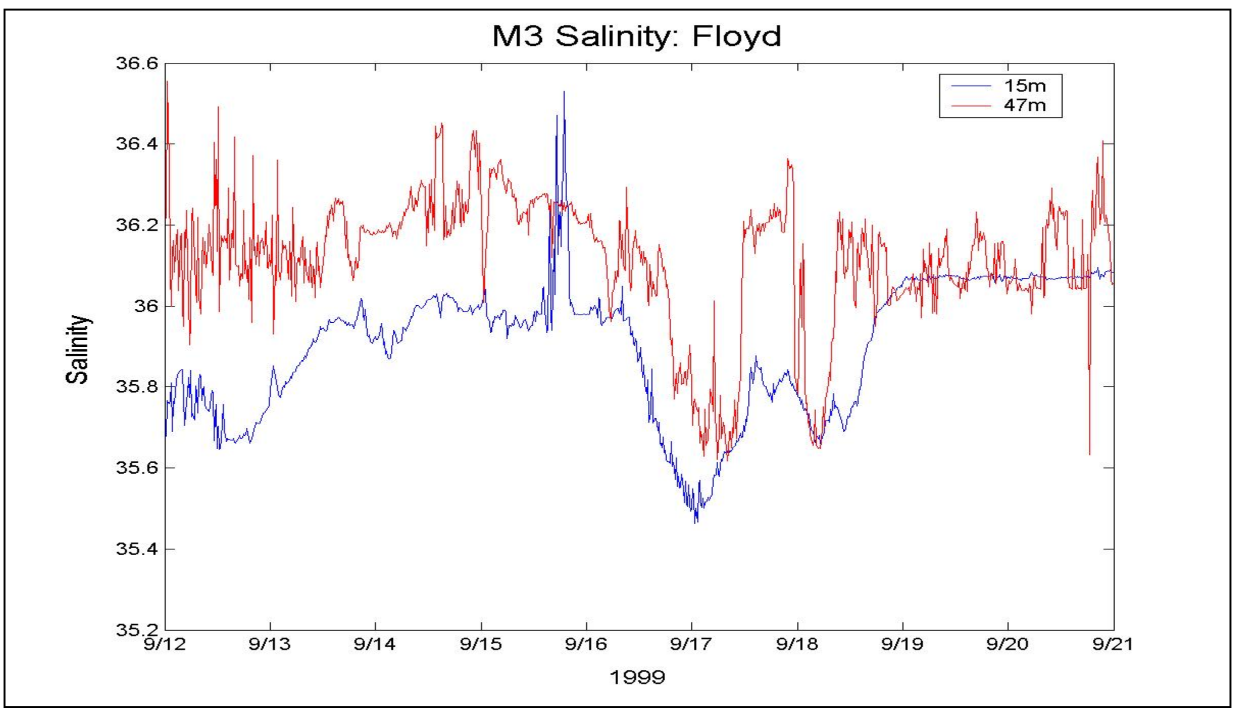

Figure 14B: Hurricane Floyd M3 Salinity

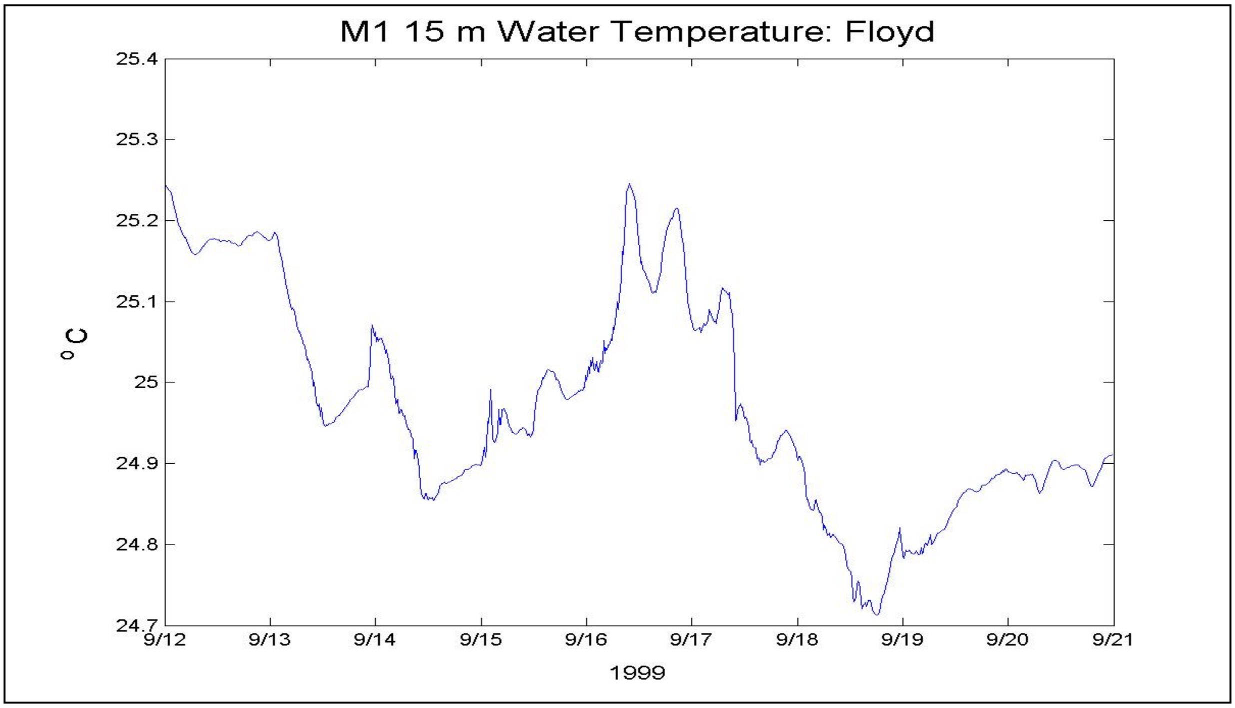

Figure 15A: Hurricane Floyd M1 Temperature

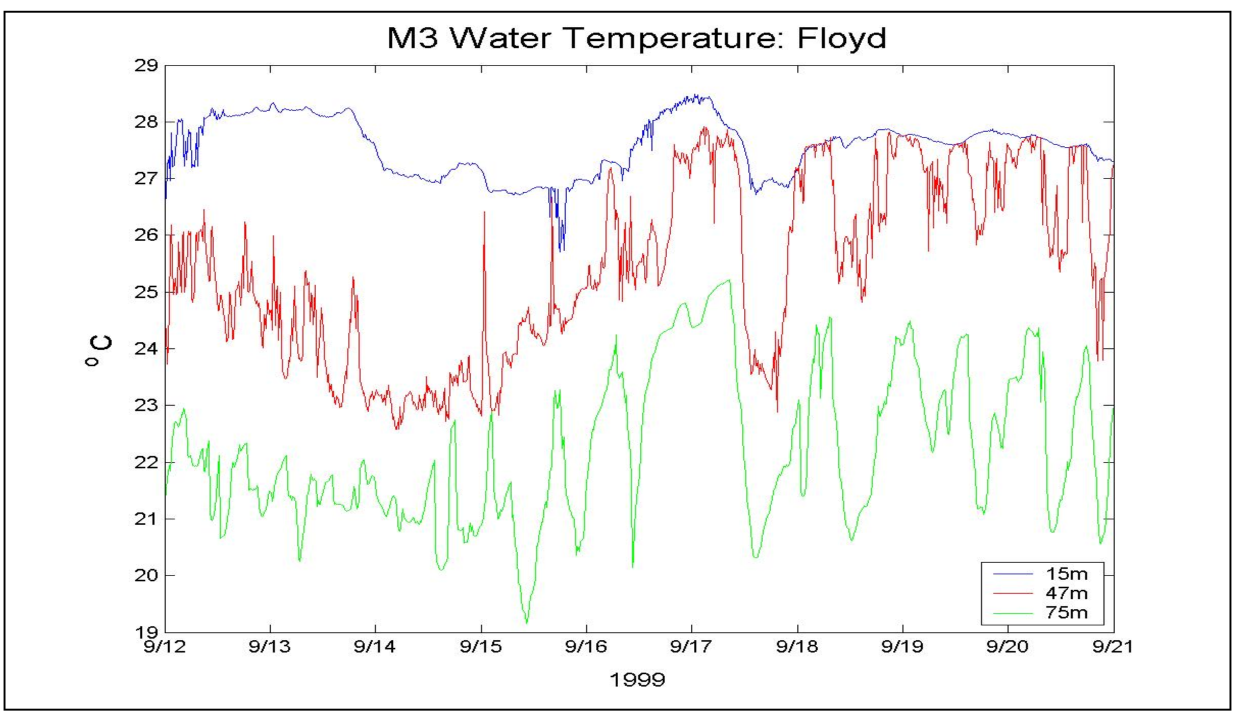

Figure 15B : Hurricane Floyd M3 Temperature

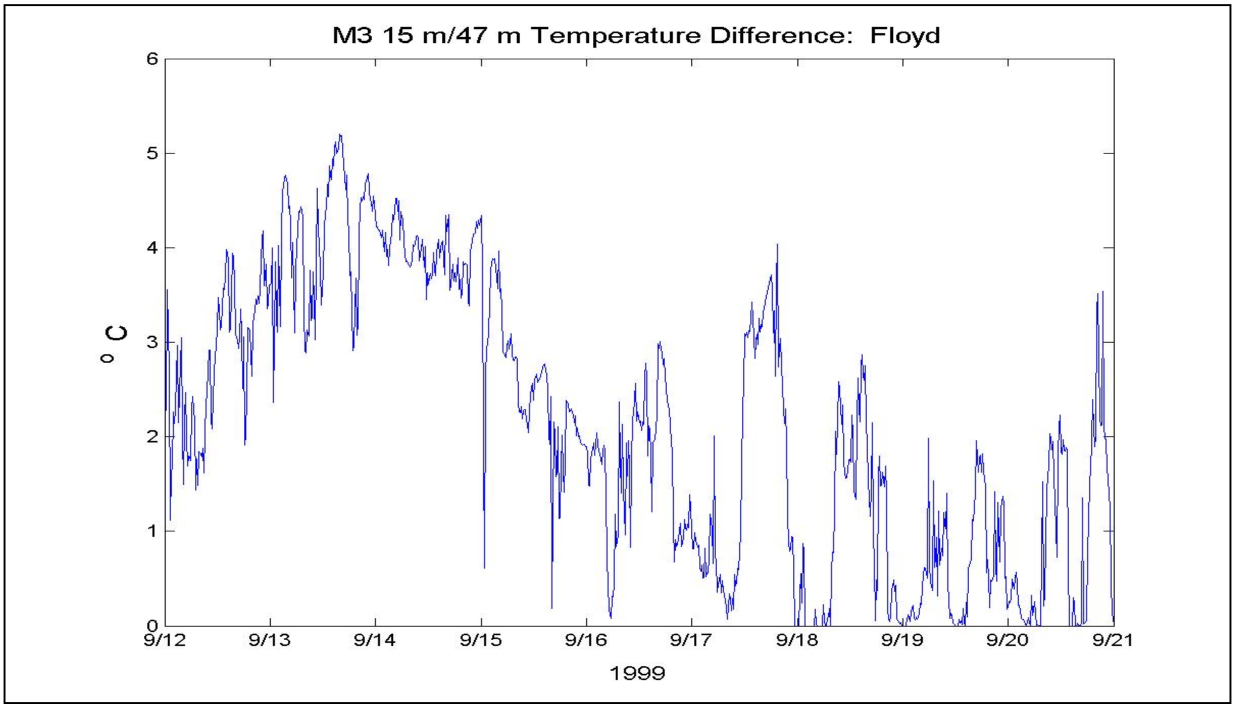

Figure 16A: Hurricane Floyd M3 15 m - 47 m Temperature Difference

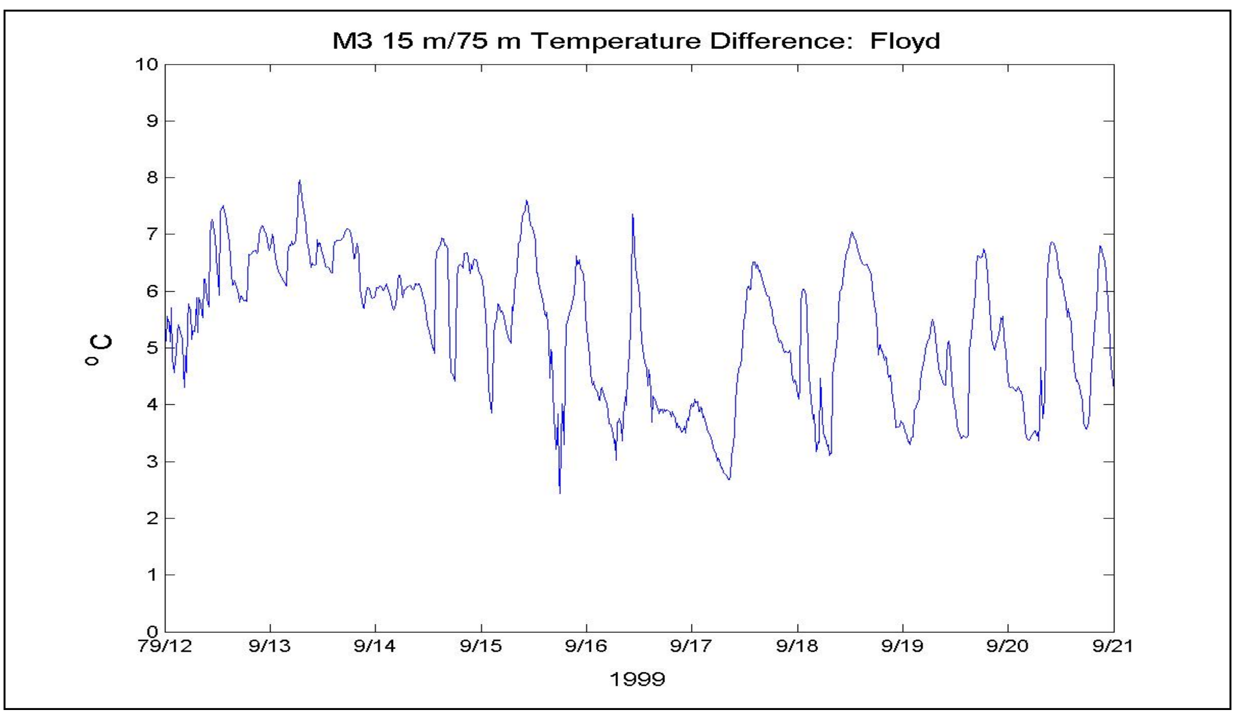

Figure 16B: Hurricane Floyd M3 15 m -75 m Temperature Difference

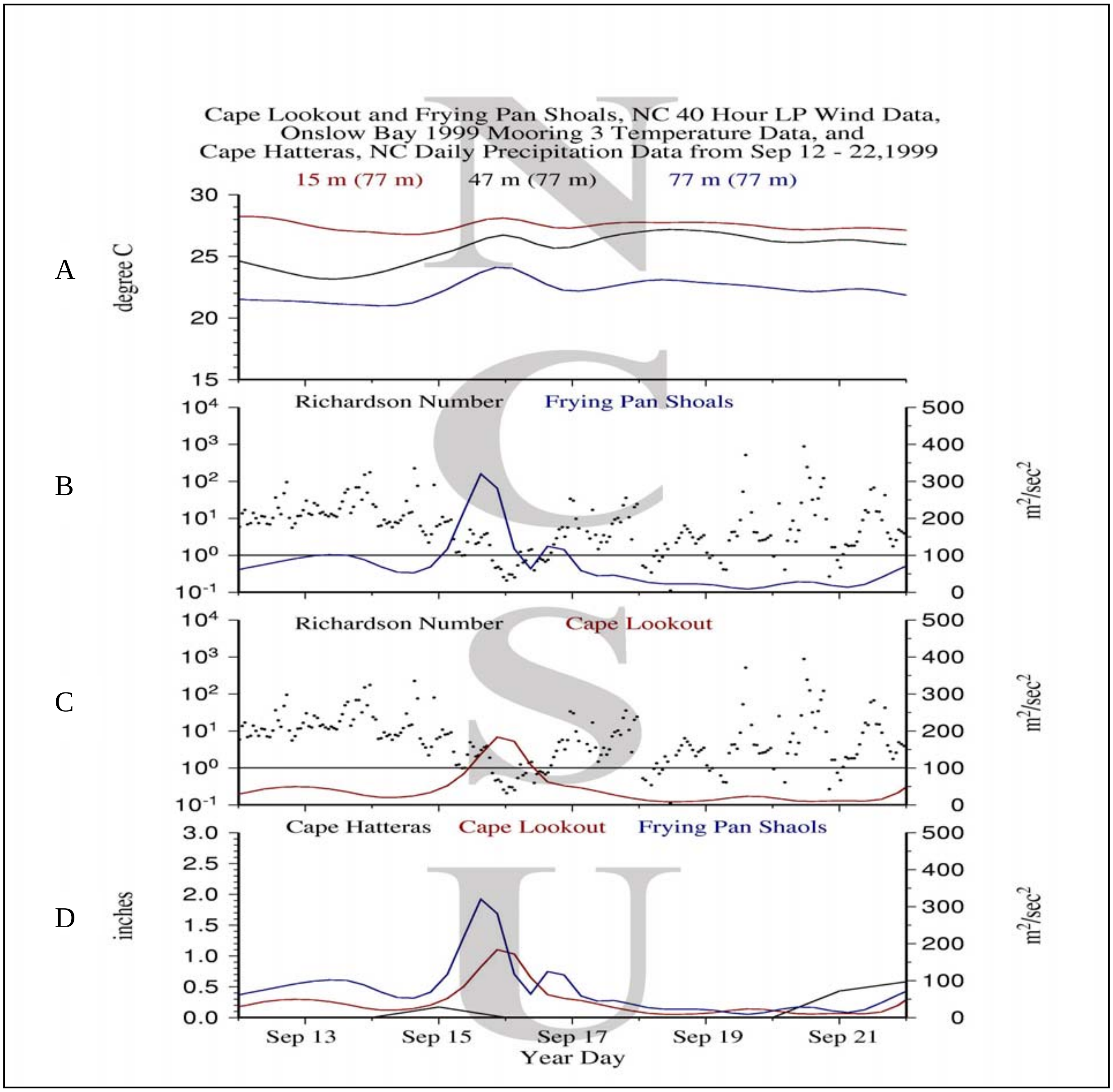

Figure 17: : All plots are 40 hour low pass (17A) Hurricane Floyd M3 Water Temperature, 15m (red), 47 m (blue), 77 m (black); (17B) M3 Richardson number between 6 m and 36 m, black dotted line indicates Ri, blue solid line is the kinetic energy of the wind speed at FPT; (17C) M3 Richardson number between 6 m and 36 m, black dotted line indicates Ri, red solid line is the kinetic energy of the wind speed at Cape Lookout; (17D) Blue line is the kinetic energy of the wind speed at FPT, , Red line is the kinetic energy of the wind speed recorded from Cape Lookout (station CLKN7), Black line is the precipitation from recorded from NOAA's NCDC station located at Billy Mitchell Airport on the island of Hatteras, NC

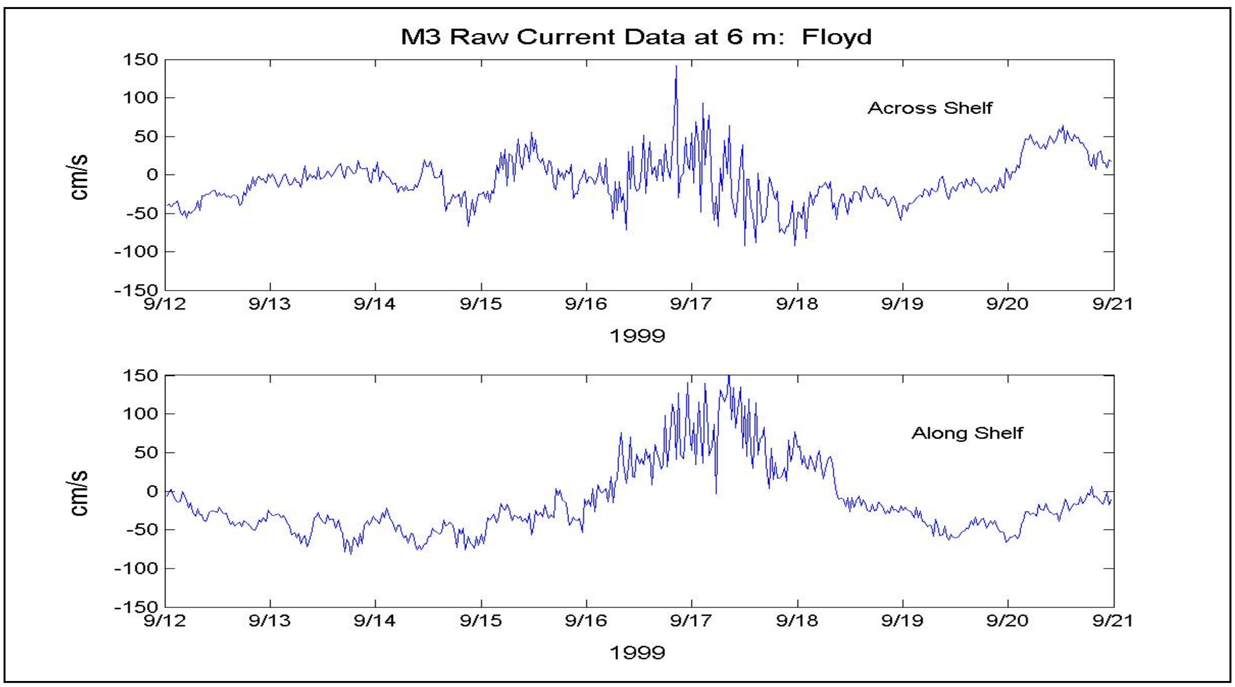

Figure 18: Hurricane Floyd M3 Raw Current Data (rotated 35˚ counter-clockwise from the x axis)

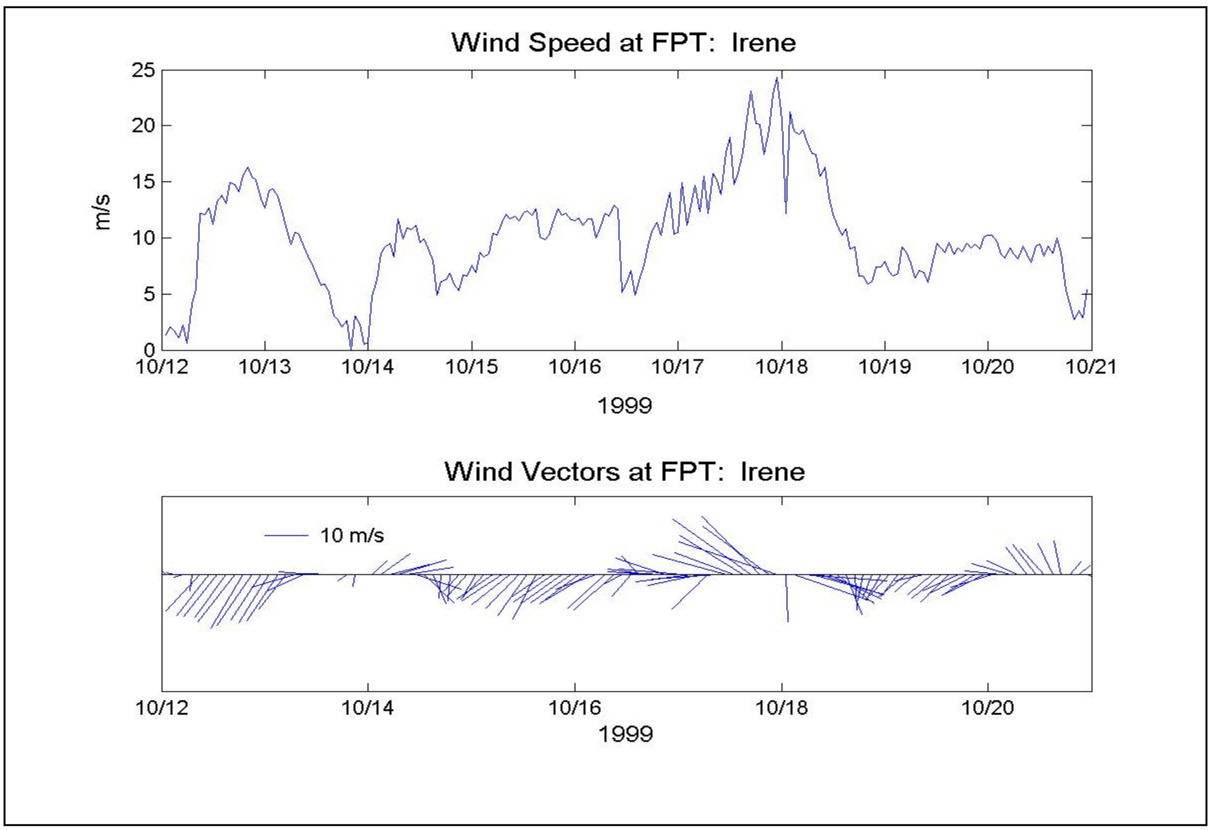

Figure 19: (Top) Hurricane Irene Wind Speed and (Bottom) Wind Vectors at FPT (north/south is the vertical and east/west is the horizontal)

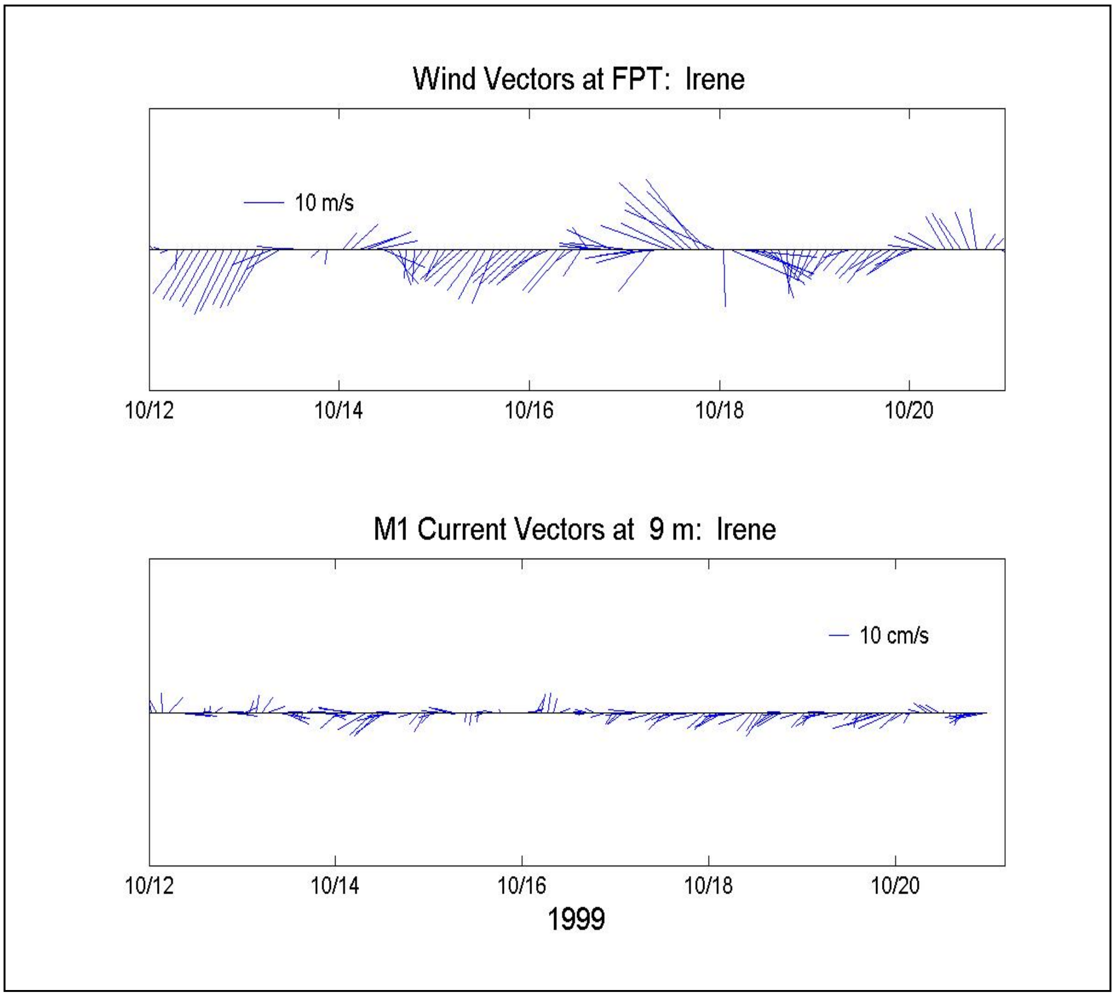

Figure 20: (Top) Hurricane Irene Wind Direction and (Bottom) M1 Current Vectors at 9m (3hour low pass, north south is the vertical axis and east/west is the horizontal axis)

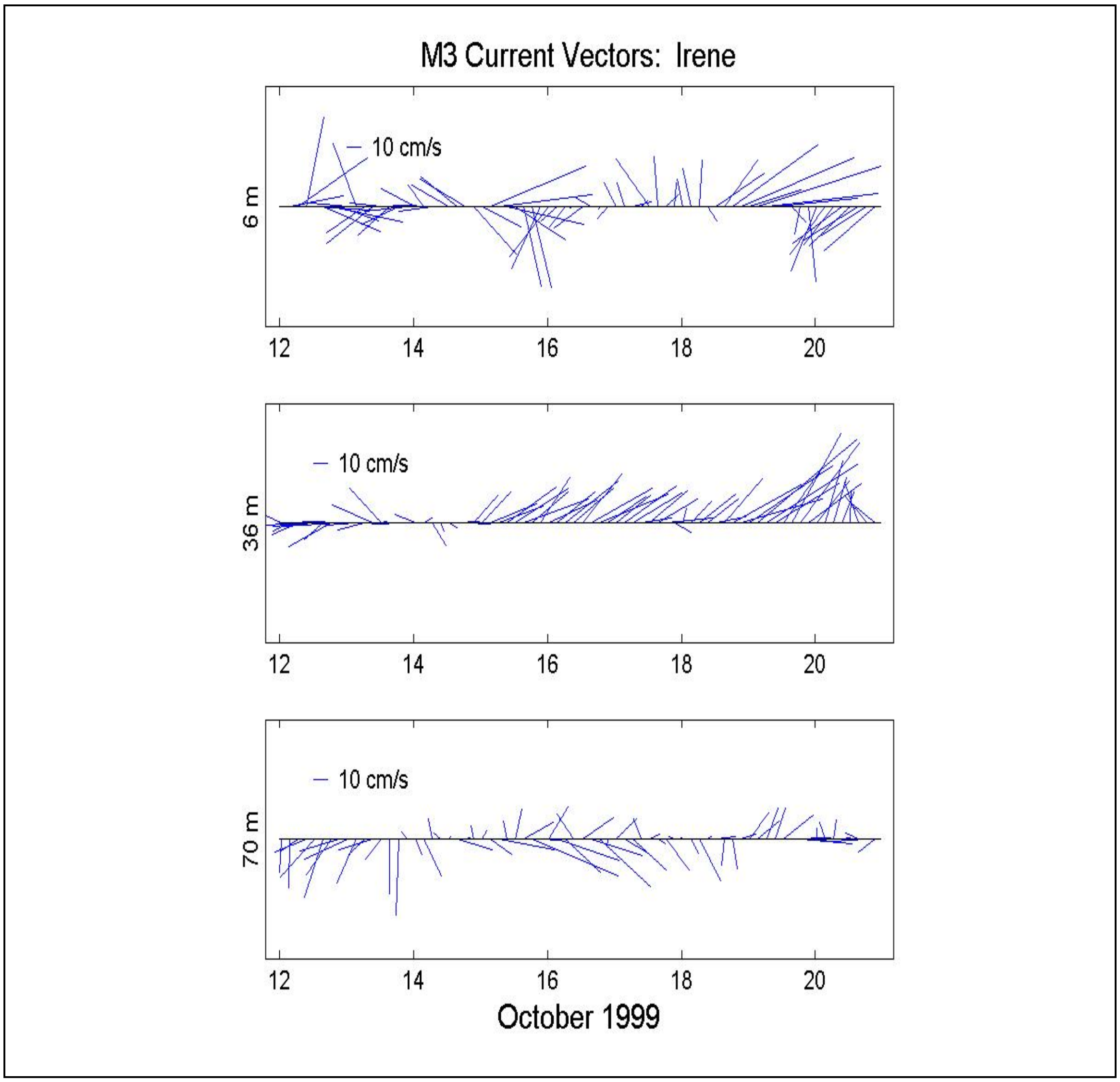

Figure 21: Hurricane Irene M3 Current Vectors (3 hour low pass, north/south is the vertical axis and east/west is the horizontal axis)

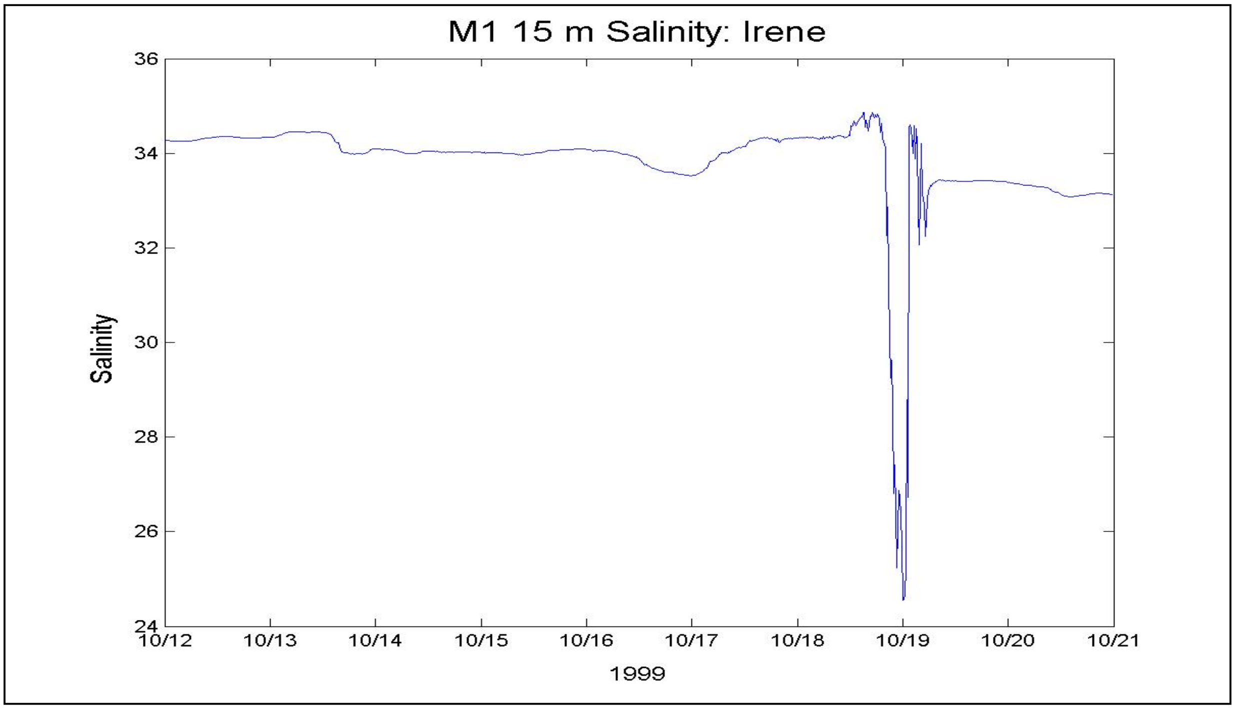

Figure 22A: Hurricane Irene M1 Salinity

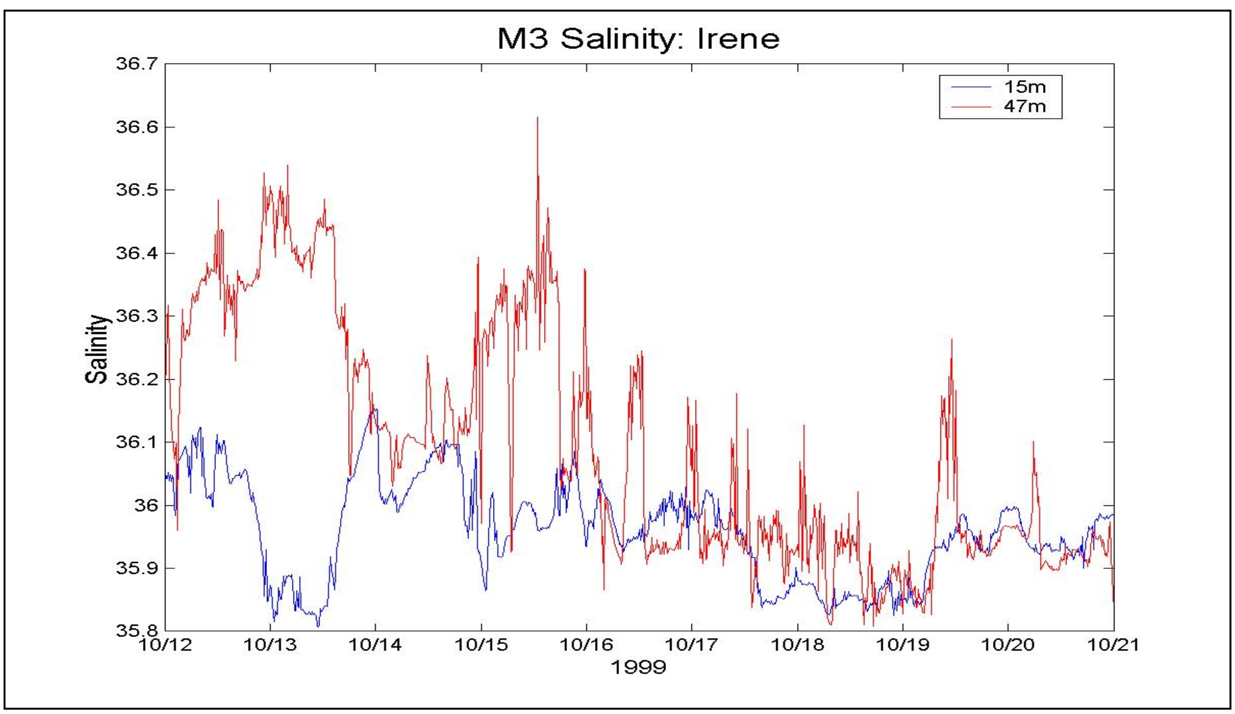

Figure 22B: Hurricane Irene M3 Salinity

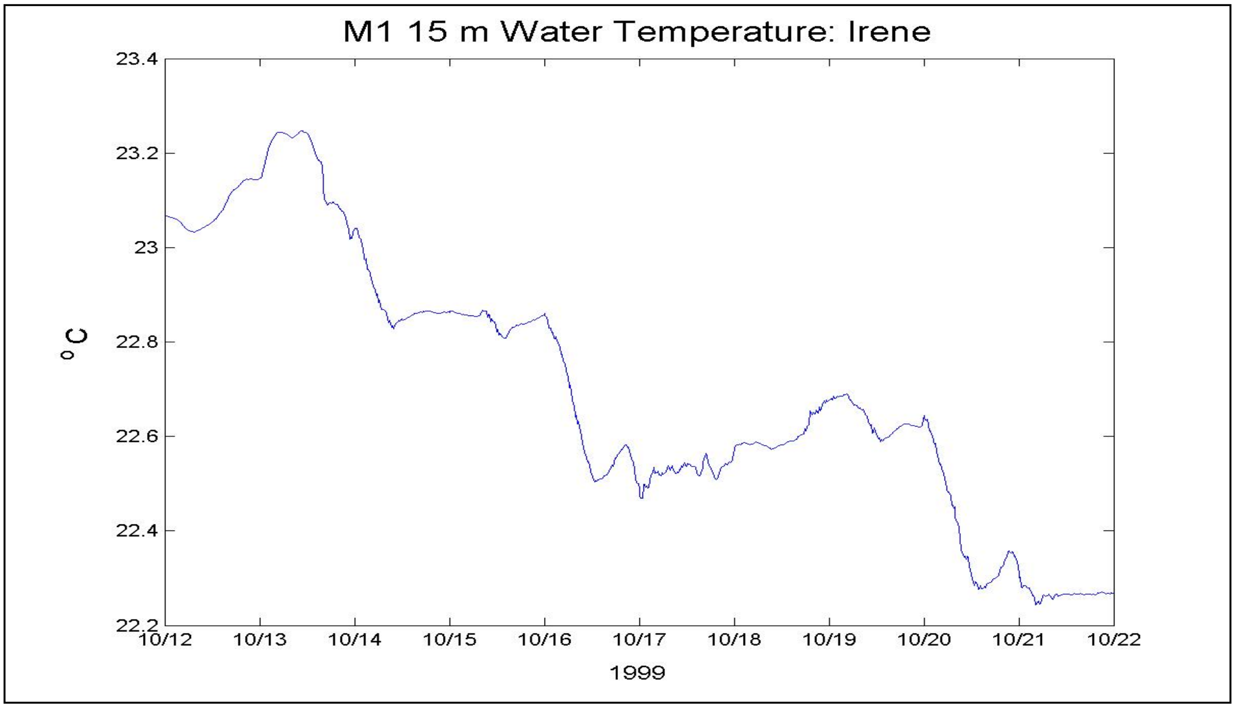

Figure 23A: Hurricane Irene M1 Temperature

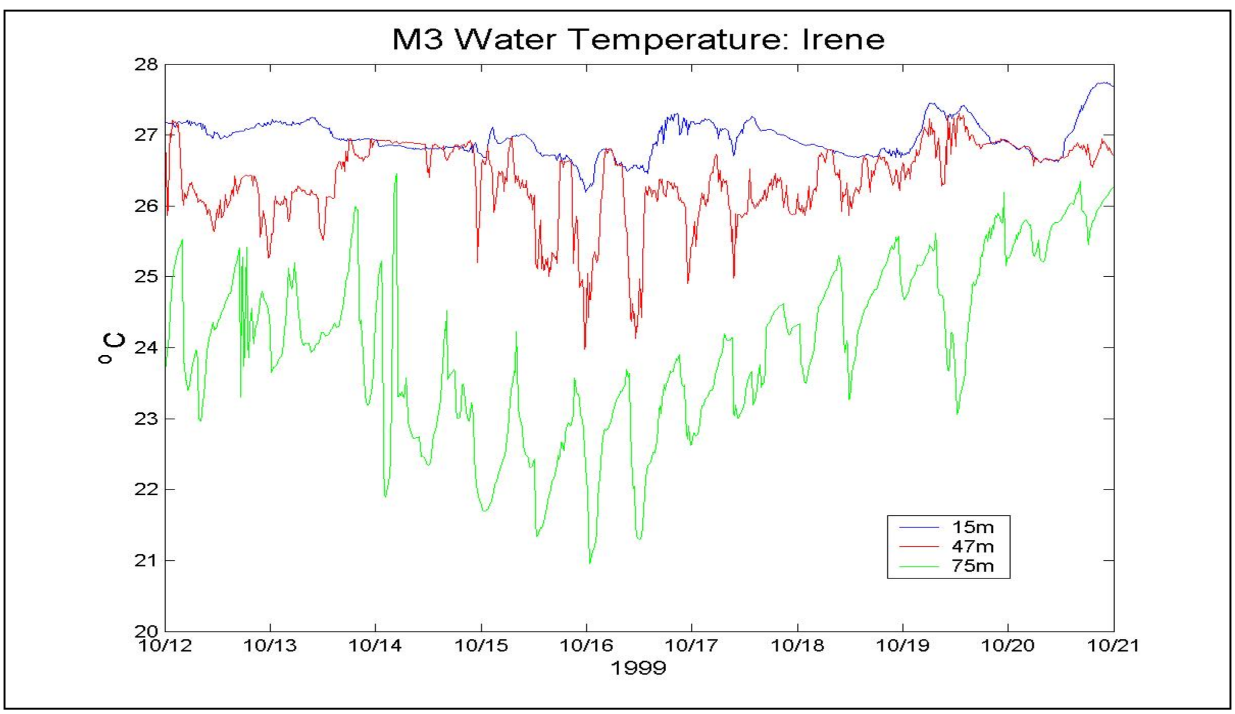

Figure 23B: Hurricane Irene M3 Temperature

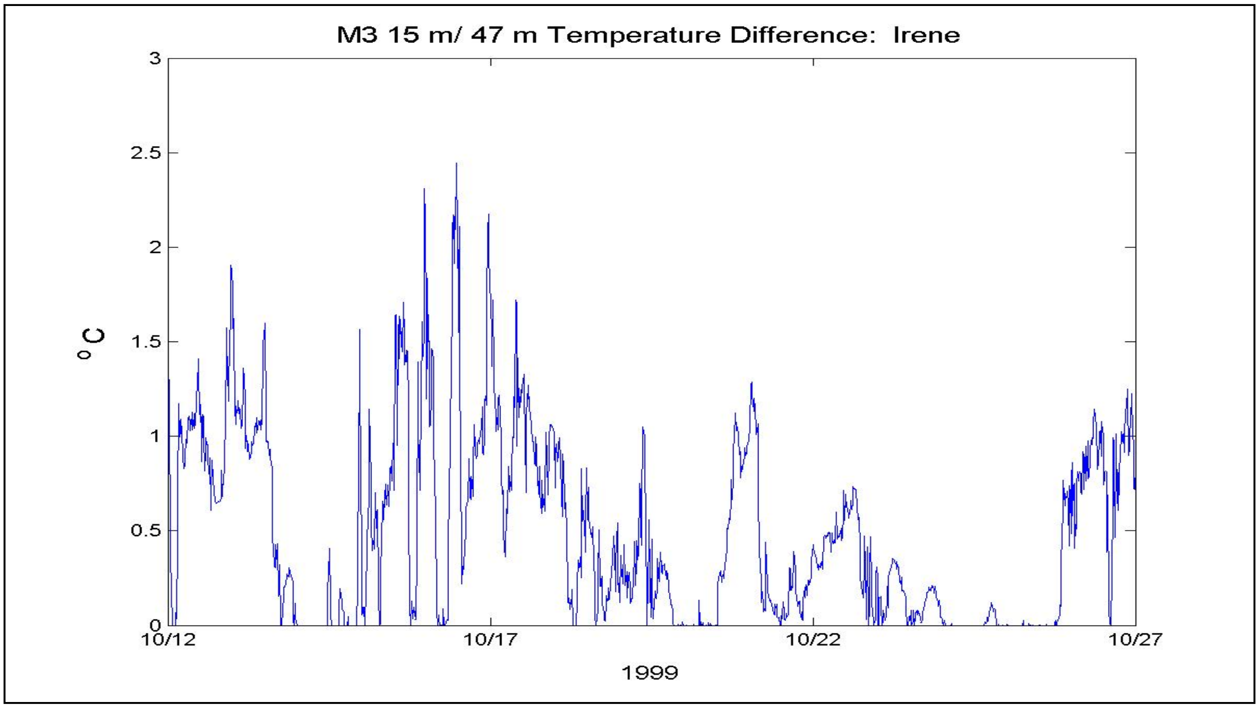

Figure 24A: Hurricane Irene M3 15 m - 47 m Temperature Difference

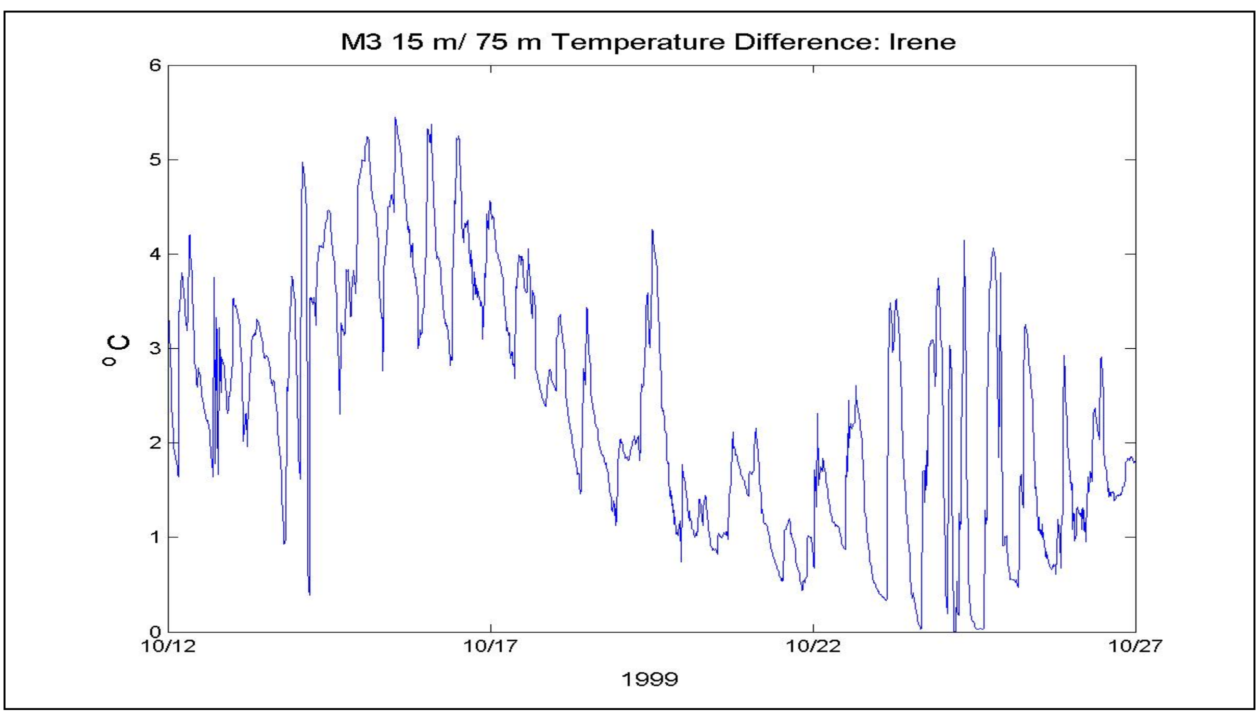

Figure 24B: Hurricane Irene M3 15 m - 75 m Temperature Difference

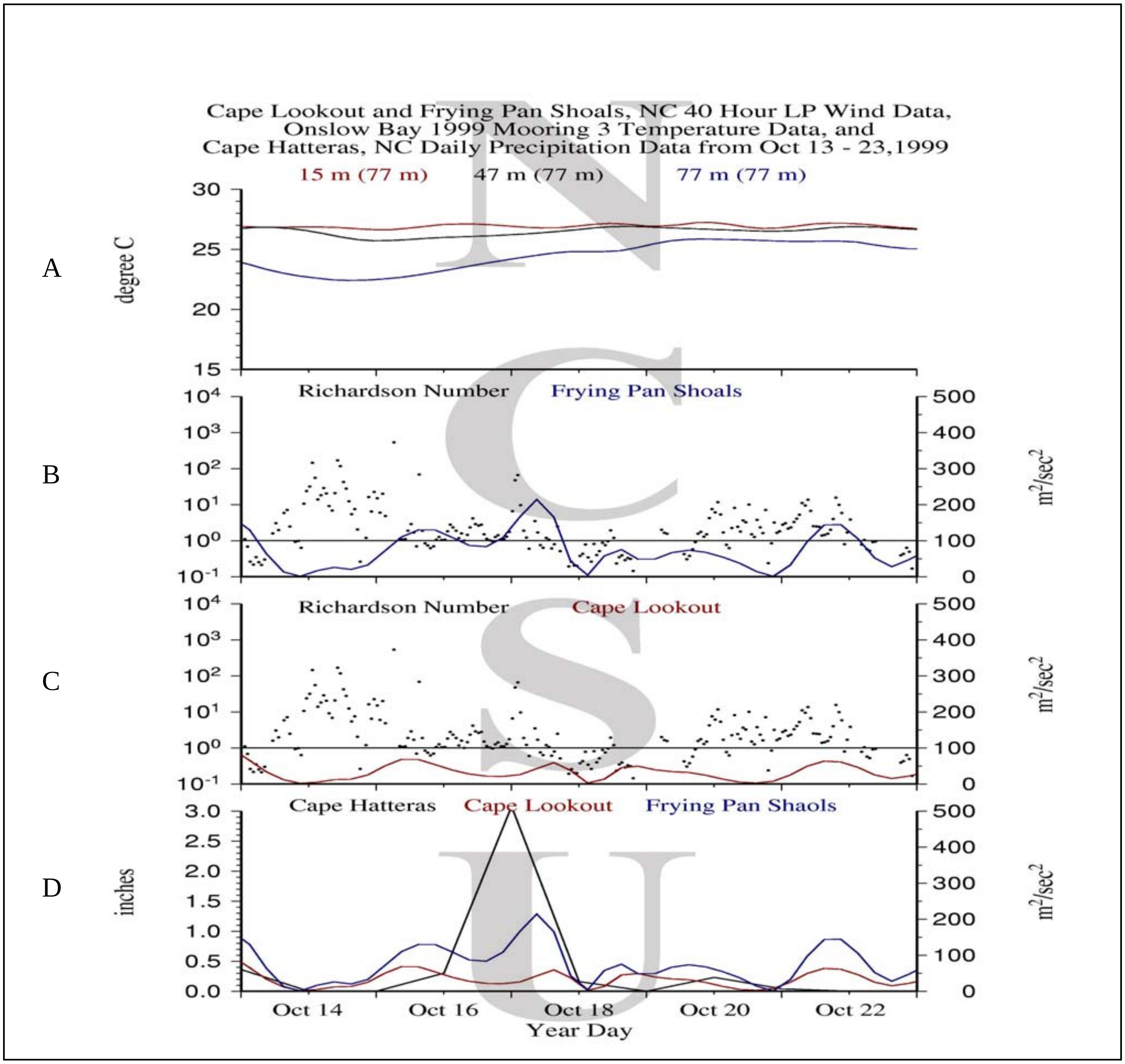

Figure 25: All plots are 40 hour low pass (25A) Hurricane Irene M3 Water Temperature, 15m (red), 47 m (blue), 77 m (black); (25B) M3 Richardson number between 6 m and 36 m, black dotted line indicates Ri, blue solid line is the kinetic energy of the wind speed at FPT; (25C) M3 Richardson number between 6 m and 36 m, black dotted line indicates Ri, red solid line is the kinetic energy of the wind speed at Cape Lookout; (25D) Blue line is the kinetic energy of the wind speed at FPT, , Red line is the kinetic energy of the wind speed recorded from Cape Lookout (station CLKN7), Black line is the precipitation from recorded from NOAA's NCDC station located at Billy Mitchell Airport on the island of Hatteras, NC

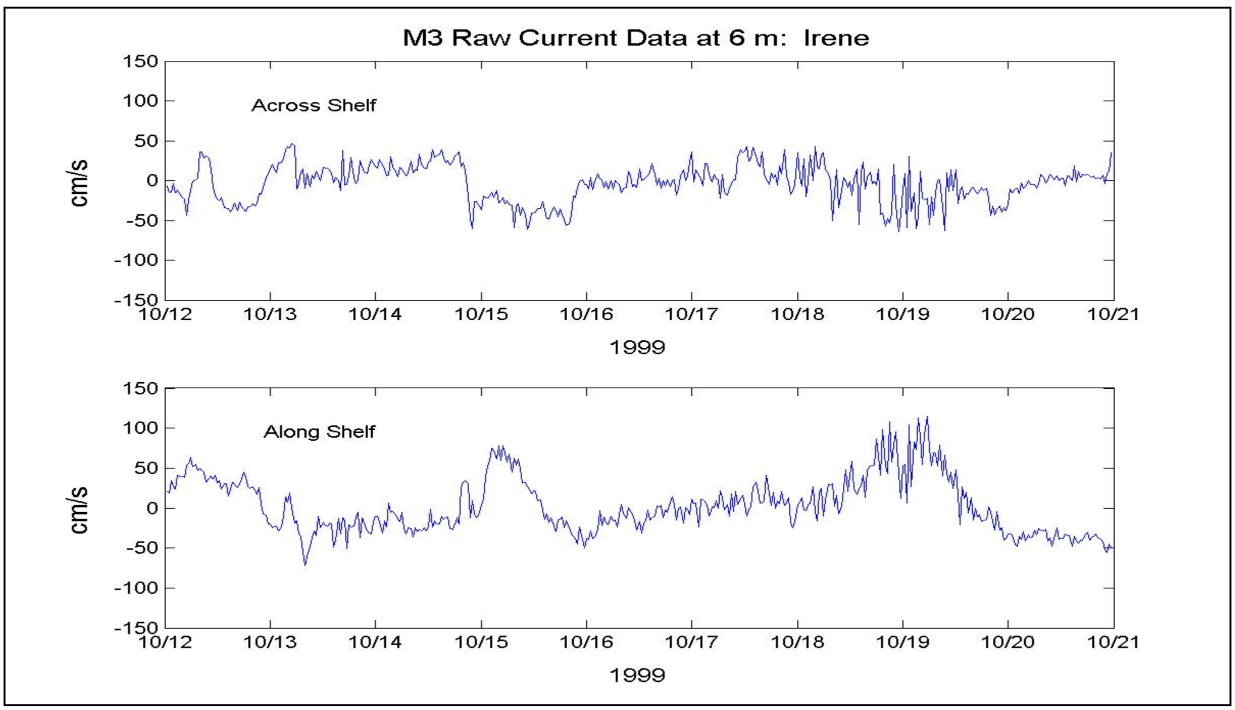

Figure 26: Hurricane Irene M3 Raw Current Data

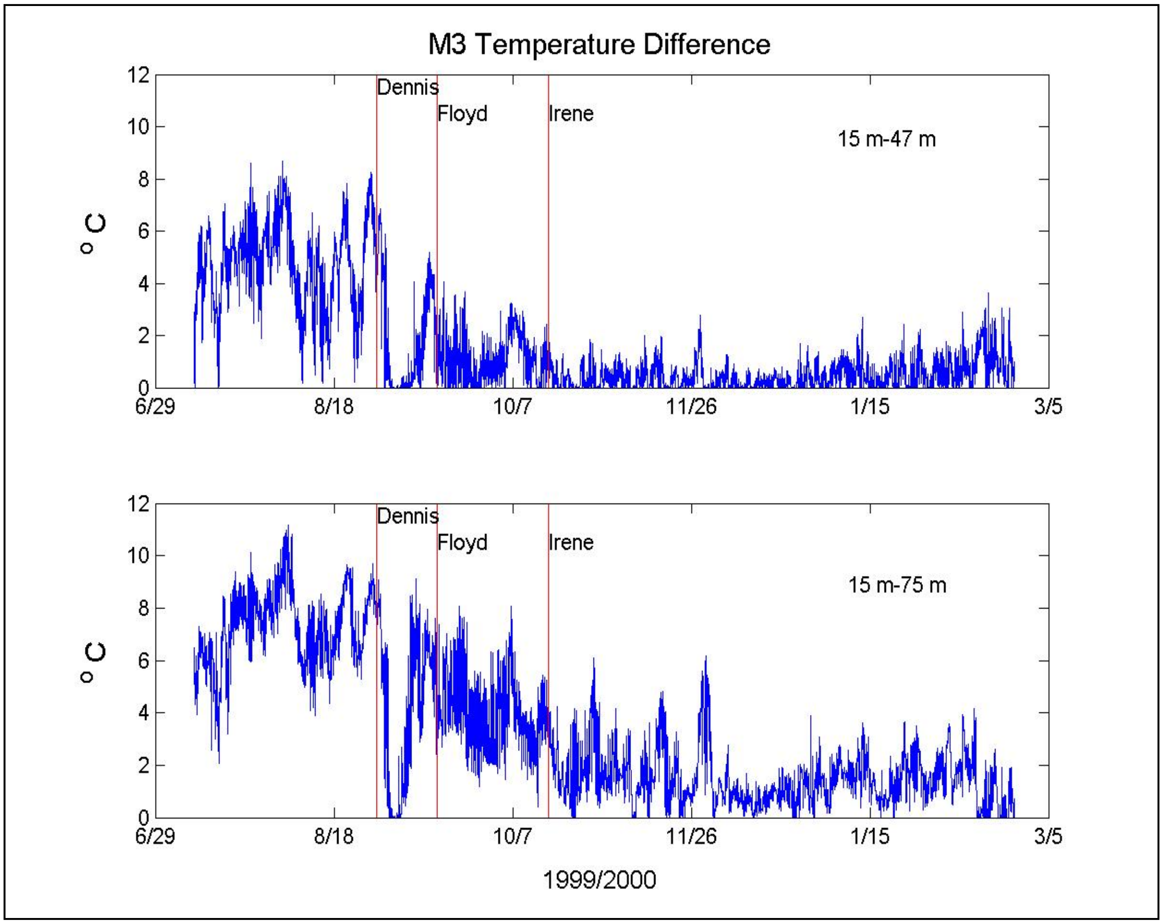

Figure 27 (Top) M3 15 m - 47 m Temperature Difference and (Bottom) M3 15 m - 75 m Temperature Difference

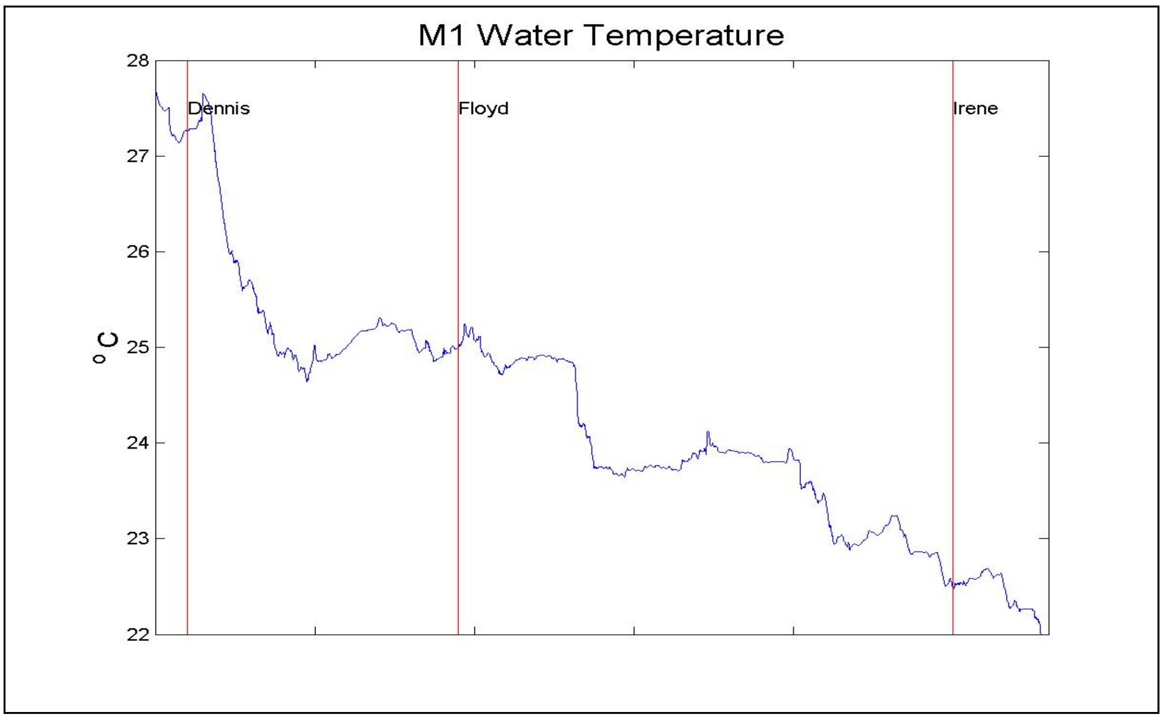

Figure 28: M1 Water Temperature at 15m from before Dennis to after Irene

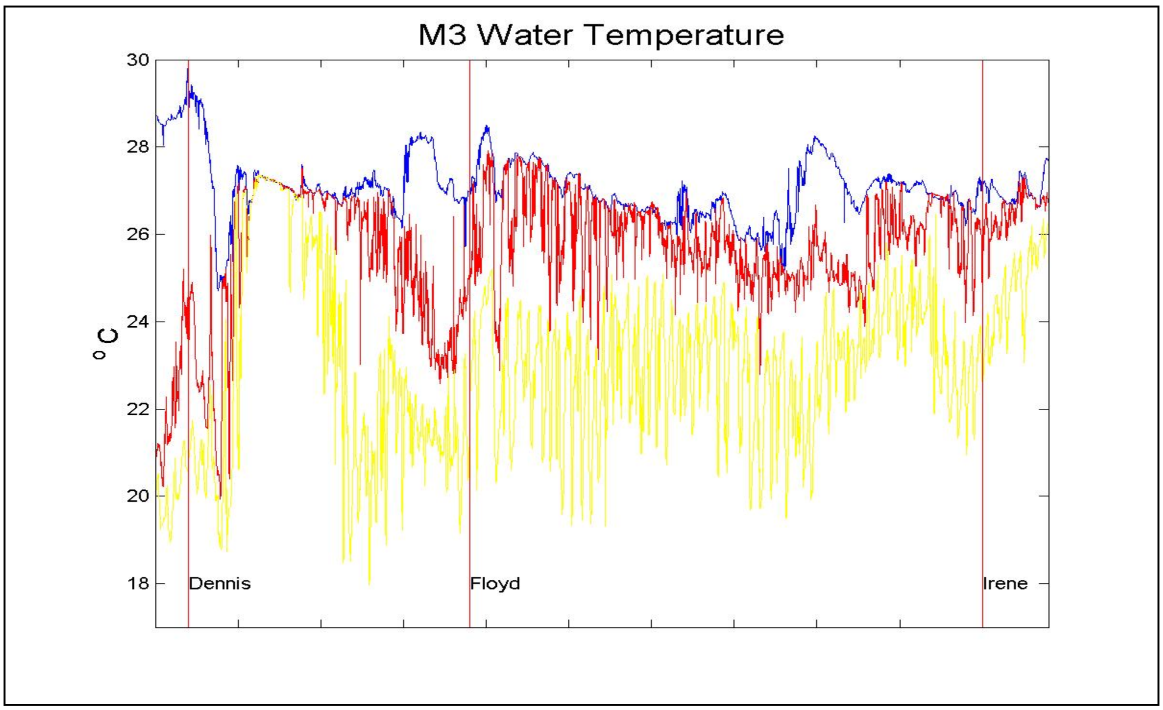

Figure 29: M3 Water Temperature from before Dennis to after Irene

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